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# Value-Added Products of Onion: Transforming the Grand Challenge into Golden Opportunities

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Onion (*Allium cepa* L.), one of the world's most important vegetable crops, faces significant post-harvest losses estimated at 23-35% in India, amounting to 6-8 million tonnes annually. Processing and value addition offer a strategic solution to these losses while creating substantial economic opportunities. This article explores the spectrum of value-added products derived from onions, including dehydrated flakes and powder, paste, puree, pickles, juice, oil, vinegar, and minimally processed products. These products extend shelf-life from weeks to 12-18 months, reduce transport volume by approximately 80%, ensure year-round availability, and generate 5-10 times value addition. With India being the world's largest onion producer and second-largest exporter of dehydrated onions, processing represents a transformative approach to addressing the "Grand Onion Challenge" while meeting growing global demand for convenience foods.

## Introduction

Onion (*Allium cepa* L.) holds an indispensable position in kitchens worldwide, adding distinctive flavour, aroma, and nutritional value to countless culinary preparations. Cultivated for over 5,000 years, this versatile vegetable has evolved from a simple dietary staple to a globally significant agricultural commodity. India stands as the world's largest onion producer, contributing approximately 27-30% of global output with an annual production of 26.4 million metric tonnes. The crop is cultivated across three distinct seasons viz., kharif, late kharif, and rabi, ensuring year-round availability in domestic markets.

However, the onion sector faces what experts call the "Grand Onion Challenge", a complex web of interrelated problems affecting all stakeholders. Post-harvest losses remain alarmingly high, with 23-35% of production lost due to microbial rotting (10-12%), sprouting during storage (8-10%), and physiological weight loss (5-6%). In absolute terms, this represents 6-8 million tonnes of onion lost annually, valued at ₹8,000-10,000 crore. The situation is exacerbated by

extreme price volatility, with wholesale rates fluctuating from ₹800 to ₹5,000 per quintal, inadequate storage infrastructure (only 30-40% of required capacity), and weather abnormalities that frequently damage standing crops.

Processing and value addition emerge as powerful solutions to these challenges. By converting raw onions into shelf-stable products, we can dramatically reduce post-harvest losses, stabilize market prices, create employment opportunities, and meet the growing consumer demand for convenience foods. The global dehydrated onion market is projected to grow at 7.2% CAGR from 2025 to 2031, driven by increasing demand for ready-to-eat meals, soups, sauces, and processed foods.

## The Spectrum of Value-Added Products from Onion

### 1. Dehydrated Products: The Crown Jewel of Onion Processing

Dehydration stands as the most important processing method for onions, transforming perishable bulbs into stable products with extended shelf-life. The



process reduces moisture content from 86-90% in fresh onions to just 4-5% in properly dehydrated products, effectively halting microbial growth and enzymatic reactions.

**Dehydrated flakes** represent the most common dehydrated product. These small, flat pieces are produced by peeling, slicing (to 3-5 mm thickness), and drying under controlled conditions. The optimal drying parameters for convection hot air drying are 76°C temperature, 27 m/min air velocity, and 3 mm slice thickness, achieving complete drying in approximately 58 minutes. Two-stage drying (90°C to 50% moisture, then 50°C to completion) can save 25% of processing time compared to single-stage drying.

**Onion powder** is produced by grinding dehydrated flakes to a fine consistency. The powder dissolves readily and reconstitutes quickly, making it ideal for seasoning blends, soup mixes, spice rubs, and baked products like bread and pizza. However, due to its hygroscopic nature, proper packaging with anti-caking agents (1-2% silicon dioxide or tricalcium phosphate) is essential to prevent moisture absorption and caking.

**Other dehydrated forms** include kibbled (coarsely chopped pieces providing textured appearance), minced (finely chopped), chopped (versatile small pieces), and rings (used in frozen convenience foods) (Fig. 1). The global dehydrated onion market is dominated by flakes and powder, which together account for approximately 70% of total volume.



Fig. 1 Dehydrated products of onion

**Quality requirements for dehydration:** For high-quality dehydrated products, onion varieties should possess:

- High dry matter (>20%, ideally up to 25%)
- High total soluble solids (>16° Brix)
- Low reducing sugars (glucose and fructose) to prevent Maillard browning
- High pungency (15-20 µmol/g pyruvic acid) as pungency declines during drying
- Single-centeredness (≥85% single-centered bulbs for ring products)
- White colour (to prevent browning from anthocyanins)

## 2. Paste and Puree: Convenient Culinary Bases

**Onion paste** is produced by crushing onions to a uniform consistency, followed by heating at 110°C to achieve 32° Brix concentration. The process incorporates 2-5% salt for taste and 0.1-0.2% citric acid for preservation. Pasteurization at 82°C for 30 seconds to 30 minutes inactivates spoilage microorganisms, and hot filling at 75-80°C with immediate sealing ensures a shelf-life of up to 18 months.

**Onion puree** has lower total soluble solids (10-15° Brix) and a thinner, more liquid consistency, making it suitable for incorporation into soups, sauces, and beverages. Double and triple-concentrated purees are produced using vacuum evaporators.

Both products serve as essential ingredients for food service and industrial applications, providing convenience while retaining authentic onion flavour.

## 3. Pickled Onions: Traditional Preservation Meets Modern Palates

Pickling remains one of the oldest and most popular preservation methods. The process involves fermenting onion bulbs in 10% brine solution for 3-4 days, during which sugars convert to lactic acid, acetic acid, and alcohols. The finished pickle is





bottled in dark vinegar with caramel and pasteurized at 80°C.

Ideal pickling onions are white, globe-shaped, with small neck and root zone, and uniform small size (2-3 cm diameter). Brown or dark red onions of 28-45 mm diameter and white or silver-skinned onions of 10-28 mm diameter are also used. Quality concerns include blemishes and white-coloured blotches in the first layer, caused by improper fermentation.

#### 4. Onion Juice and Oil: Concentrated Nutritional Powerhouses

**Onion juice** is produced by flash heating crushed pulp at 140-160°C, immediate cooling to 40°C, and evaporation to 72-75% solids for preservation. The juice contains valuable flavonoids including quercetin, rutin, and myricetin, which have been shown to reduce cholesterol levels, elevate antioxidant activity, inhibit lipid peroxidation, and increase the oxidation period of low-density lipoprotein cholesterol.

**Onion oil** is obtained by distillation of minced onion, with the minced onion allowed to stand at ambient temperature for several hours before distillation to complete enzymatic reactions. The yield is very low (0.002-0.03%), meaning approximately 4.4 kg of fresh onion yields only one gram of onion oil. The dark amber-coloured liquid exhibits strong antimicrobial properties, effective against gram-positive bacteria, mycotoxin-producing fungi, and dermatophytic fungi. Sulfur compounds in onion oil demonstrate antibacterial, antioxogenic, and antidermatophytic activity.

#### 5. Specialty Products

**Onion vinegar** is produced by fermenting onion juice with *Acetobacter aceti* culture. The product contains exceptionally high potassium (943 mg), low sodium (54 mg), and high calcium (363 mg) and magnesium (122 mg) compared to conventional vinegars. Onion vinegar boosts the immune system, provides probiotics and digestive enzymes, and is effective against hypertension.

**Onion wine and beverages** represent emerging products with growing market interest, capitalizing on onion's sugar content through fermentation processes.

**Minimally processed products** including fresh-cut onions and frozen onion rings cater to the convenience food market. Fresh-cut onions require modified atmosphere packaging (2% O<sub>2</sub> + 10% CO<sub>2</sub>) to extend shelf-life while maintaining quality. Frozen onion rings have a storage life of 12 months and can be directly used for consumption or as ingredients in prepared foods.



Fig. 2 Diverse value-added products from onion

#### Nutrient Enhancement Through Processing

The nutrient composition of onion undergoes dramatic concentration during dehydration. Per 100 grams, dehydrated onion contains significantly higher levels of essential nutrients compared to fresh onion (Table 1).

**Table 1: Comparative nutrition status of Fresh vs. Dehydrated Onion**

| Nutrient     | Fresh Onion | Dehydrated Onion | Fold Increase |
|--------------|-------------|------------------|---------------|
| Protein (g)  | 1.2         | 10.6             | 8.8×          |
| Calcium (mg) | 46.9        | 300.0            | 6.4×          |
| Iron (mg)    | 0.6         | 32.0             | 53.3×         |
| Vitamin C    | 11.0        | 147.0            | 13.4×         |





|                 |       |        |      |
|-----------------|-------|--------|------|
| (mg)            |       |        |      |
| Potassium (mg)  | 127.0 | 1000.0 | 7.9× |
| Magnesium (mg)  | 16.0  | 104.0  | 6.5× |
| Molybdenum (mg) | 0.03  | 2.29   | 76×  |

The dramatic increases in mineral concentrations make dehydrated onion a highly nutrient-dense ingredient. However, on a per-serving basis, the absolute nutrient intake from dehydrated onion may be lower because serving sizes are typically smaller.

### Economic Impact and Market Opportunities

The economic benefits of onion processing are substantial:

1. **Value addition:** Fresh onions fetch ₹15-25/kg at farm gate, while dehydrated powder can command ₹150-250/kg. Even after the 10:1 shrinkage ratio, value addition remains substantial.
2. **Export potential:** India is the second-largest producer of dehydrated onions globally, accounting for nearly 30% of global trade with annual revenue of approximately USD 115.5 million. Major export destinations include the European Union, Japan, Russia, Germany, Netherlands, Spain, and United Kingdom.
3. **Employment generation:** Processing units create employment opportunities in manufacturing, quality control, packaging, logistics, and distribution networks.
4. **Reduced post-harvest losses:** Processing can recover a significant portion of the 6-8 million tonnes currently lost annually, turning waste into wealth.

The global dehydrated onion market is projected to grow drastically, driven by increasing demand for

convenience foods, growth in the food service sector, and rising awareness of shelf-stable ingredients.

### Indian Success Stories and Varietal Development

India has made significant progress in developing processing-specific onion varieties:

- **ICAR-DOGR**, Pune, through 20+ years of recurrent selection, has improved the population from only 0.7% of bulbs having TSS >15% in 2000 to 98% of bulbs now having TSS >15%, with elite lines achieving TSS >18%.
- **Bhima Super** achieved 95% single-centered bulbs through eight cycles of phenotypic selection, demonstrating that sustained selection can improve traits with low heritability.
- **Arka Lalima and Arka Kirthiman** (IIHR, Bengaluru) are F1 hybrids specifically identified for paste production.
- **PWO-2** (PAU, Ludhiana) is a processing-grade white onion with TSS 14-16% and dry matter 25%, suitable for rabi season cultivation.

### Challenges and the Way Forward

Despite the immense potential, several challenges hinder the growth of onion processing in India:

- Inadequate storage infrastructure (only 30-40% of required capacity)
- Lack of processing-grade varieties with high dry matter (>20%)
- High capital costs for processing equipment
- Quality inconsistencies due to varying raw material quality
- Limited awareness among farmers about processing-specific cultivation

**Future directions** include:

- Development of core breeding populations for processing traits



- Adoption of doubled haploid techniques to overcome inbreeding depression
- CRISPR-based genome editing for trait improvement
- Integration of IoT-enabled real-time quality monitoring
- Promotion of decentralized, small-scale processing clusters
- Public-private partnerships for infrastructure development

### Conclusion

Onion processing and value addition represent a transformative opportunity to address India's "Grand Onion Challenge" while creating substantial economic value. The spectrum of products, from dehydrated flakes and powder to paste, pickles, juice, oil, and vinegar, offers diverse market opportunities with 5-10 times value addition compared to fresh onions.

By extending shelf-life from weeks to 12-18 months, reducing transport volume by 80%, ensuring year-round availability, and generating employment, processing addresses the core challenges facing the onion sector. India's position as the world's largest onion producer and second-largest exporter of dehydrated onions provides a strong foundation for leadership in the global processed onion market.

The way forward requires integrated efforts in breeding processing-specific varieties, developing appropriate technologies, creating infrastructure, fostering public-private partnerships, and building farmer awareness. With growing global demand for convenience foods and shelf-stable ingredients,

onion processing offers a golden opportunity to transform an age-old crop into a modern success story, benefiting farmers, processors, consumers, and the nation's economy alike.

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# Bio-herbicide for eco-friendly weeds management

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Weeds are the main factor lowering crop production. Chemical herbicides are quite effective for managing weeds and may get rid of them to a large extent; but, as resistance grows, these herbicides become less effective. It is necessary to find an appropriate replacement to chemical herbicides. Bio-herbicides are soon-to-be-available products for for a long time weed control. A bio-herbicide is a novel weed-management technique derived from naturally occurring plant or living organism compounds. Bio-herbicides contain microorganisms, including pathogens from bacteria, viruses, and fungi, as well as plant-based materials like essential oils and plant extracts. The bio-herbicide interferes with biological processes like photosynthesis and respiration as well as cellular functions like hormone and toxin eradication, cell wall and membrane integrity, and food intake. To help with the economic commercialization of various biological herbicides, many formulations have been developed to increase their shelf life.

## Introduction

Unwanted plant populations, or weeds, compete with the primary plant for resources and are a major factor in low agricultural yields. Following World War II, the advent of 2,4-D and MCPA, two selective herbicides, significantly decreased weed losses without endangering the primary crop. Despite selectivity, weed resistance issues have been documented despite the discovery of 25 herbicide sites. To solve the issues with weed management and maintaining agricultural production, new control technologies must be continuously developed.

There are several approaches to managing weeds, including both direct and indirect techniques. By inhibiting the weed's ability to grow vegetatively and reproduce, indirect approaches weaken it. Using physical, mechanical, biological, or chemical means to eradicate the weed plant is known as a "direct method" of weed control. These weed management techniques currently in use have certain drawbacks and are insufficient for maintaining the sustainability of contemporary farming methods. As a result, innovative techniques for effectively and

environmentally friendly controlling weeds are being researched.

Biological weed control is a strategy that limits the germination and expansion of weed populations to a level that is economically feasible by using biological enemies, natural chemicals, or biotic agents. Although the pathogenic fungus for myco herbicides is "inoculated" by spraying the microbes onto target weeds, the administration processes for bio and conventional herbicides are comparable. Recently, bioherbicides have been acknowledged as a significant part of weed control—not as a total substitute for conventional herbicides, but as an additional option. Because sustainable farming does not depend on a single weed management method, unlike synthetic herbicides in traditional agriculture, bio-herbicides should be used in concert with other weed management techniques in order to effectively control weeds.

## Definition

A **bioherbicide is a biologically based control agent for weeds**. Bio-herbicides are made up of





microorganisms (e.g. bacteria, viruses, fungi) and certain insects (e.g. parasitic wasps, painted lady butterfly) that can target very specific weeds. The microbes possess invasive genes that can attack the defense genes of the weeds, thereby killing it.

Bio-herbicides may be compounds derived from microbes or phytotoxic plant residues, extracts or single compounds derived from other plant species.

A bio-herbicide based on a fungus is called a myco-herbicide. In the industry, bio-herbicides and other bio-pesticides are often referred to as "naturals".

### Classification of bio herbicides

Bio-herbicides may be classified on the basis of their source as given below:-

#### 1. Pathogens -

- a. Fungal
- b. Viral
- c. Bacterial

#### 2. Plant by products

- a. Allelochemicals,
- b. Plant extracts
- c. Essential oil

#### 1. Pathogenic bio herbicides:-

These are bio herbicides that suppress weeds by using harmful microorganisms such as fungi, bacteria, or viruses. These bacteria have been chosen precisely for their capacity to infect and kill weeds while being safe to crops.

Pathogenic bio herbicides outperform conventional herbicides in several ways. They are frequently more environmentally friendly because they do not emit hazardous substances into the environment. They can also be more targeted, as they can be developed to eliminate certain weeds.

#### A. Fungal Pathogens as bio-herbicides:-

Fungi are the most common plant pathogens for weed control. Fungal pathogens are the most promising alternative of synthetic chemical herbicides for weed management systems. Fungal pathogens weed control is based on their phytotoxic metabolites. *Alternaria*, *Ascochyta*, *Drechslera*, *Phoma*, *Phyllostictica*, *Pyrenophora*, *Septoria*, *Stagonospora*, are the most common fungal pathogens for the bio-control of weeds like *Chenopodium album* L., *Cirsium arvense* L., grass weeds etc.

#### B. Viruses as Bio-herbicides:-

Viruses can also be used as bioherbicides in controlling some weeds but due to some constraints they are not effective as fungal pathogens. Viruses have lots of genetic variability and are not target specific. Tobacco mosaic tobamovirus (TMV), a most popular virus, this virus has potential to kill the tropical soda apple (*Solanum viarum*).

**Examples** - *Araujia* Mosaic Virus, Tobacco Rattle Virus, Óbuda Pepper Virus (ObPV) and Pepino Mosaic Virus (PepMV)

#### C. Bacteria as bio-herbicides:-

Many bacteria have been proved as potential bio-control agent for weeds due to some characteristic features like growth cultures can be maintained in liquid, prepared as dry formulation and can be genetically modified to improve the bio-efficacy

**Examples** - *Pseudomonas fluorescens* strain BRG100, *Pseudomonas fluorescens* strain D7, *Xanthomonas compestris* and *Streptomyces hygroscopicus*

#### 2. Plants as bio-herbicides:-

Many plant based products are also utilized as potential natural agent for weed control. Plants have secondary metabolites or other photochemicals which show inhibit seed germination and other growth processes. The plant products can be used as weed controlling agent in three forms i.e. plant extract,



essential oil and allelochemicals. These three plant products have been using as potential bio-herbicides from last so many decades. This primary mode of action of plant based products is the inhibition of germination of weeds and reduction of plant growth.

**Essential oils examples-** *Artemisia absinthium* L., *Brassica napus*, *Eucalyptus citriodora* Hook, *Eucalypt* (*Eucalyptus nicholii*), *Rosemary* (*Rosmarinus officinalis* L.), *Lawson cypress* (*Chamaecyparis lawsoniana*) and *White cedar* (*Thuja occidentalis*) plants

**Table No. 1. Registered bio-herbicides (pathogens) for weed control**

| Registered bio-herbicides    | Pathogen name                                             | Targeted Weed                                                                                                                                         |
|------------------------------|-----------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------|
| Devine <sup>TM</sup>         | <i>Phytophthora palmivora</i>                             | <i>Morrenia odorata</i>                                                                                                                               |
| Collego <sup>TM</sup> (1982) | <i>Colletotrichum gloeosporioides</i>                     | <i>Aeschynomene virginica</i>                                                                                                                         |
| Biomal <sup>R</sup>          | <i>Colletotrichum gloeosporioides</i>                     | <i>Malva pusilla</i>                                                                                                                                  |
| Wood Warrior <sup>R</sup>    | <i>Puccinia thlaspeos</i>                                 | <i>Isatis tinctoria</i>                                                                                                                               |
| Mycotech <sup>TM</sup>       | <i>Chondrostereum purpureum</i>                           | <i>Prunus serotina</i><br><i>Populus euramericana</i>                                                                                                 |
| Smoulder <sup>R</sup>        | <i>Sclerotinia minor</i>                                  | Dicot weeds                                                                                                                                           |
| Comperico                    | <i>Xanthomonas campestris</i>                             | <i>Poa annua</i> L.<br>In turf                                                                                                                        |
| Organo – sol <sup>R</sup>    | <i>Lactobacillus casei</i><br><i>Rhizobium lactis</i> sp. | <i>Trifolium repens</i> L.,<br><i>Trifolium pratense</i> ,<br><i>Lotus corniculatus</i> L.<br><i>Medicago lupulina</i><br><i>Oralis acetosella</i> L. |

|                                                  |                                                              |                                      |
|--------------------------------------------------|--------------------------------------------------------------|--------------------------------------|
| Pselouka <sup>R</sup>                            | <i>Rape seed oil nonanoic acid</i><br><i>Pelargonic acid</i> | Weeds of potatoes, grape weeds       |
| Chontrol <sup>TM</sup><br>Ecoclear <sup>TM</sup> | <i>Chondrostereum purpureum</i>                              | Alders and other hardwoods in forest |
| Dr. bio seed                                     | <i>Puccinia caniculata</i>                                   | <i>Cyperus esculantus</i>            |
| Slumpout <sup>TM</sup>                           | <i>Cylindrobasidium leave</i>                                | <i>Acacia</i> Sp.                    |

### Constraints of Pathogens as Bio-herbicide:-

There are many limitations of using pathogens as bio-herbicide such as environmental, biological, economic or commercial constraints and technological.

#### 1. Biological limitations

Most desirable factor for weed controlling agent is the host specificity. It has been discovered that many pathogens are capable to control only one weed species.

**2. Environmental limitations:-** Environmental factors are also among the primary factors that influence formulation performance of bio-herbicides as inoculum production is dependent on spore relation of the formulation. This process, although rapid, might continue over several weeks subsequent to applications and might encounter variable environmental conditions.

The most important environmental factors of foliarly applied bio-herbicides are:-

- Moisture (dew)
- Bio-herbicide application time
- Formulations
- UV radiations, Humidity, and rain water.



### 3. Technological limitations

Several technological constraints have been identified that could prevent the widespread use of bio-herbicides. Pathogenical strains, formulation method and the interaction of these two parameters significantly affect the shelf-life of the formulations at room temperature. The ability to produce fungal biomass in large-scale fermentation and to formulate it into readily useable material is very essential.

### 4. Commercial/economic limitations

Microbial herbicides are not economically sound because of deficiency of promising techniques of mass production and synthesis for microbial

**5. Human-related constraints:** Procedural errors (the human factor) are frequently the sources of failures in bio-herbicide. As the number of personnel lacking experience and expertise in bio-herbicide has grown, local failures have increased. Lacking of adequate training and provision of information to secondary users are also play a significant human related constraint in using bio-herbicide in weed management.

### Formulations of Bio-Herbicide:-

Bio-herbicide formulation is the blending of active ingredient and inert materials for effective delivery of herbicide dose to the targeted host weed plant. Formulated products of bio-herbicides are very useful to improve application, survivability, efficacy and maintaining viability during storage and reduce moisture requirement for germination.

### Types of bio-herbicide formulations

#### 1. Liquid formulations

a . Nvert emulsion

b. Suspoemulsion

#### 2. Solid formulation

a. Wettable powder

b. Granular formulation

### 1. Liquid formulation:-

These are sprayable formulations these formulations include suspension emulsions, emulsions and polymer based products. In these formulations water is the transporting medium and adjuvants used assist the active ingredient transport in weed plants.

### 2. Solid formulation:-

These formulations are applied in soil basically in simple formulations like granular and encapsulated forms. Inert material includes grains, clay alginate, charcoal, polymers etc. These are most suitably used as pre-emergence application and can give longer period of activity as controlled release formulation. Solid formulations have higher shelf life than liquid formulations. Granular formulations can give 75% weed control.

### Benefits in using bio-herbicide:

There are several advantages- No buildup of chemical residues or pollution of the environment. It adopts a more sustainable and environmentally aware posture. Herbicide resistance can also be linked to research on the creation of bioherbicides. The research done by Ash, Cother, and coworkers received some assistance from the target weed's emergence of synthetic pesticide resistance. They demonstrated how the fungus *Plectosporium alismatis* may be able to suppress weeds in Australia's rice fields. *P. alsimatis* and particular herbicides cooperating may result in reduced herbicide application rates.

### Conclusion

The loss in productivity of crops is mostly due to weeds, which are also a major obstacle to feeding the world's expanding population. Bio-herbicides are not used in agricultural practises, even if they are sustainable and safe. To increase the efficacy of bio-herbicides and bring them to market, more study and development are required. Host specificity is a major concern because bio-herbicides do not effectively eradicate a broad variety of weed species in the field.



Bioherbicides ought to be employed in tandem with a comprehensive approach to circumvent critical concerns like resistance and host specificity. The main weed control tool for promoting organic farming may be bio-herbicides. Consequently, a number of novel formulation techniques can raise the bioherbicide's effectiveness. A formulation utilizing a variety of different bio control agents should be developed to target a broad spectrum of weed species.

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# Determinants of Drone Technology Adoption in Agriculture: A Systematic Review of Behavioral and Socio-Economic Drivers

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The integration of drone technology into agriculture holds immense potential for enhancing precision, efficiency, and sustainability. This review examines the multifaceted factors influencing farmers' adoption of unmanned aerial vehicles (UAVs) in agricultural practices based on current literature. Drawing on recent empirical studies, it evaluates the predictive power of behavioral models, the current levels of awareness and knowledge among farmers, and the socio-economic drivers and barriers shaping adoption decisions. Despite the abundance of fragmented empirical studies, there is a lack of synthesized literature that maps these findings onto established behavioral frameworks. While perceived behavioral control, time savings, and labor scarcity strongly motivate adoption, significant constraints remain, including high initial costs, lack of technical expertise, and infrastructural limitations. Targeted interventions, such as training programs and government subsidies, are essential to facilitate wider acceptance.

## 1. Introduction

Sustainable agriculture is increasingly reliant on innovative technologies to address global food security challenges, resource depletion, and climate change. Precision agriculture, which optimizes resource utilization while minimizing environmental impacts, has been revolutionized by the introduction of drone technology. Unmanned Aerial Vehicles (UAVs), commonly known as drones, enable high-resolution data collection, precise pesticide application, and real-time crop monitoring. Despite these significant benefits, the widespread adoption of agricultural drones by farmers is not uniform and depends on a complex web of psychological, social, and economic factors (Nafar, Fatemi, & Rezaei-Moghaddam, 2026; Sundar, Asokhan, & Karthikeyan, 2023). This review synthesizes current research on farmers' awareness, perceptions, and the underlying behavioral models driving the adoption of agricultural drones. This review was conducted by synthesizing peer-reviewed empirical studies published between 2023 and 2026, focusing on behavioral economics and agricultural technology diffusion.

## 2. Behavioral Models of Drone Adoption

Understanding the psychological and social factors behind technology acceptance is crucial for facilitating broader adoption. Recent research evaluates several predictive models to map farmer behavior (Nafar, Fatemi, & Rezaei-Moghaddam, 2026):

- **Technology Acceptance Model (TAM):** Highlights perceived usefulness and perceived ease of use as key determinants of attitudes and intentions toward drone adoption.
- **Theory of Planned Behavior (TPB):** Incorporates social influences and perceived control. Studies show that behavioral intention and perceived behavioral control are highly influential in distinguishing drone adopters from non-adopters.
- **Communicative Learning Model (CLM):** Emphasizes social interaction, peer influence, and communication channels in the diffusion of innovations.



- **Unified Adoption Behavior Model (UABM):** Integrating TAM, TPB, and CLM provides the most robust predictive power (yielding up to 91.2% classification accuracy) for identifying drone adopters. Adopters consistently exhibit higher behavioral intention, better access to communication channels, and a stronger perception of behavioral control.

Having established the theoretical basis for adoption, it is necessary to examine how these models translate into the practical realities of farmer awareness and field application.

### 3. Farmers' Awareness and Knowledge Gain

Farmers' awareness of specific drone applications varies and is heavily influenced by regional practices and local farming systems (Raveendran et al., 2023).

- **High Awareness Applications:** Agrochemical spraying is the most recognized application globally. Studies across regions like Gujarat and Tamil Nadu indicate that 70.53% to 75% of farmers are highly aware of drones' utility for precise pesticide and fertilizer application (Kalsariya et al., 2025; Murugan, Dhivya, & Senthilkumar, 2024). Pest/disease control and irrigation management also show significant baseline awareness (60%–68%).
- **Knowledge Gain through Demonstrations:** Formal training and field demonstrations significantly enhance operational knowledge. In the Cuddalore district, post-demonstration knowledge gain was highest in pest/disease monitoring (71.67%) and sowing/planting operations (71.17%) (Hanif & Natarajan, 2025).
- **Low Awareness Applications:** Farmers remain largely unaware of advanced, data-driven niche applications such as yield estimation (33.68%), real-time livestock monitoring (25.26%–28%), and multispectral crop mapping (42.11%) (Kalsariya et al., 2025; Murugan, Dhivya, & Senthilkumar, 2024).

### 4. Drivers and Barriers to Adoption

The transition to drone-assisted farming is shaped by an interplay of economic, social, and personal factors. The following table summarizes the primary catalysts and impediments identified in the literature.

**Table 1: Summary of Drivers and Barriers to Agricultural Drone Adoption**

| Factor Category | Primary Driver                   | Primary Barrier                      |
|-----------------|----------------------------------|--------------------------------------|
| Economic        | Profit margins, input savings    | High initial capital costs           |
| Social          | Labor scarcity, peer influence   | Lack of trained, local operators     |
| Technical       | Task automation, precision       | Infrastructure/Connectivity gaps     |
| Personal        | Time-saving, scientific interest | High learning curve/Technical jargon |

- **Economic & Social Drivers:** High labor wages and scarcity are paramount; 84.26% of respondents cite labor shortages as a primary influencer (Sundar, Asokhan, & Karthikeyan, 2023). Peer observation and social influence further accelerate willingness to adopt.
- **Personal Factors:** Time-saving is a massive incentive, with 95.74% of farmers reporting reduced time consumption. Scientific orientation and a desire to save physical energy also correlate with higher adoption rates.
- **Operational Constraints:** Beyond financial hurdles, the lack of local maintenance infrastructure and the requirement for



specialized licensing pose significant long-term risks for early adopters (Kalsariya et al., 2025).

### 5. Conclusion

Drone technology offers transformative solutions for modern agriculture, particularly in mitigating acute labor shortages and optimizing chemical application. While foundational awareness is strong, institutional efforts must now shift toward disseminating knowledge regarding advanced data-monitoring features. The literature suggests that adoption behavior is heavily dictated by perceived behavioral control and immediate economic benefits.

To bridge the gap between awareness and adoption, stakeholders should focus on:

1. **Scaling "Drone-as-a-Service" (DaaS) models** to mitigate high upfront capital requirements.
2. **Expanding extension programs** to include technical training on data-driven applications.
3. **Investing in rural maintenance infrastructure** to support long-term sustainability.

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# Impacts of Microplastic Pollution on Soil Quality and Crop Productivity

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Microplastics are tiny plastic pieces smaller than 5 millimeters. They have become a hidden problem in farm soils across the world. These particles enter the soil in several ways from plastic mulches that break down from wastewater used for irrigation, from sewage sludge applied as fertilizer, and even from plastic dust carried in the air. Once inside the soil, microplastics do real damage. They change how soil behaves making it denser, less porous, and worse at holding water. They also carry toxic chemicals and heavy metals, which plants can absorb and pass up the food chain. On the biological side, microplastics harm earthworms, disturb helpful microbes, and slow down the natural enzyme activities that keep soil healthy. All of this leads to poorer soil fertility, weaker plant growth, lower crop yields, and a real threat to food security. This article looks at where microplastics come from, how they harm the soil, and what we can do to reduce the damage.

## 1. Introduction

Between 1950–1970, agriculture expanded plastic use including mulches, greenhouse covers, drip irrigation, and packaging (Qi et al., 2018). Researchers documented adverse effects on seed germination, plant growth, and crop yield representing a direct threat to soil health and global food production. Quantitative studies report 1,810 to 86,330 microplastic particles per kg of contaminated agricultural soil (Boots et al., 2019). Fundamental plant-soil interactions sustaining productivity are progressively disrupted by these persistent particles.

## 2. Sources and Pathways

Microplastics are fragments <5 mm (de Souza Machado et al., 2018). They originate from breakdown of mulch films, irrigation pipes, greenhouse covers, and packaging (Qi et al., 2018). Primary entry pathways: direct application of farming plastics, untreated wastewater irrigation, sewage sludge (biosolids), and atmospheric deposition. Degradation periods range from decades to centuries depending on polymer type and conditions (Xu et al., 2020). This persistence causes progressive accumulation and chronic exposure to soil biota and crops.

## 3. Mechanisms of Degradation

Microplastics cause harm through physical, chemical, and biological mechanisms (Boots et al., 2019).

**Physical Effects:** Reduce porosity, increase bulk density (compacting soil), decrease water infiltration and holding capacity, induce hydrophobicity (especially polypropylene and polyethylene) causing faster drying.

**Chemical Effects:** Act as vectors for toxic additives (phthalates, BPA, PBDEs) that leach into soil (Xu et al., 2020). Adsorb heavy metals cadmium (Cd), copper (Cu), lead (Pb), zinc (Zn). Plants absorb these through roots, leading to accumulation in edible tissues and human food chain entry (Wang et al., 2020).

**Biological Effects:** Earthworms consuming microplastics show reduced feeding, weight loss, and increased mortality (Boots et al., 2019). Soil microbes nitrogen-fixing bacteria (*Rhizobium* spp.), nitrifying bacteria (*Nitrosomonas*, *Nitrobacter* spp.), mycorrhizal fungi show reduced diversity and activity (Rillig & Lehmann, 2020). Key soil enzymes (urease, dehydrogenase, alkaline phosphatase) show depressed activity.





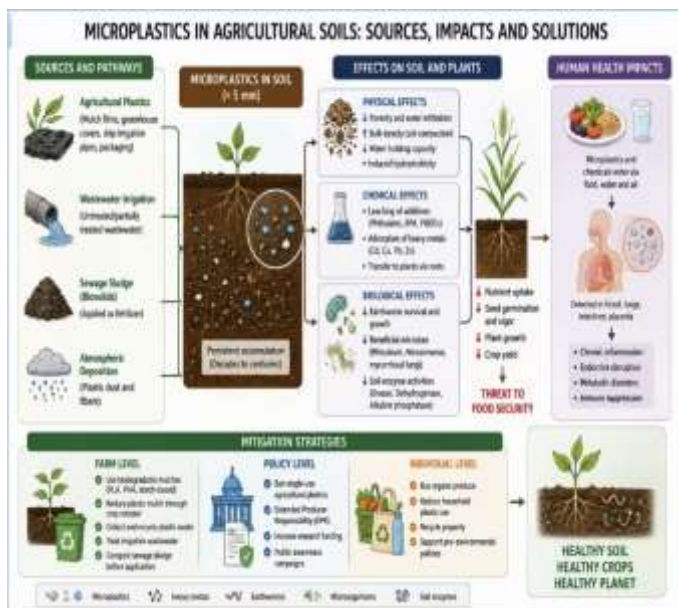


Figure 1. Micro plastic in agricultural soil from different sources and their impact on soil health

#### 4. Impacts on Nutrient Cycling & Plant Growth

Microplastics suppress nitrifying and mineralizing microorganisms, slowing conversion of organic nitrogen to plant-available ammonium and nitrate. Nitrogen immobilization causes chlorosis (leaf yellowing), stunted growth, and reduced photosynthesis. Seed germination rates decline, seedling vigor decreases, and crop yields are significantly reduced. Farmers apply more synthetic nitrogen fertilizers, increasing costs. Excess nitrogen is lost as ammonia (air pollution, respiratory disease) or leaches into water bodies causing eutrophication algal blooms, fish kills (Wang et al., 2020).

#### 5. Soil Chemical Properties

Microplastics induce soil pH shifts toward increased acidity depending on polymer type and degradation state. Acidification reduces nutrient availability, increases aluminum toxicity, and constrains acid-sensitive crops. Adsorption-desorption dynamics of essential nutrients (phosphorus, potassium, magnesium) are altered, with reduced nutrient retention and increased leaching losses (Wang et al., 2020).

#### 6. Human Health Implications

Microplastics and chemical additives enter human body through contaminated crops, animal products, inhalation of dust, and drinking polluted water (Rillig & Lehmann, 2020). Human biomonitoring detected microplastics in blood, lung tissue, intestines, and placenta (Xu et al., 2020). Adverse health outcomes include chronic inflammation, metabolic dysregulation, endocrine disruption, and immune suppression (Wang et al., 2020). Six major plastic polymer classes in agricultural soils polyethylene (PE), polypropylene (PP), polyvinyl chloride (PVC), polystyrene (PS), polyethylene terephthalate (PET), polyamide (PA) each have distinct toxicological profiles (de Souza Machado et al., 2018).

#### 8. Mitigation Strategies

**Farm level:** Replace conventional mulches with biodegradable alternatives (PLA, PHA, starch-based). Reduce plastic mulch through crop rotation. Implement plastic waste collection and recycling. Treat irrigation wastewater. Compost sewage sludge before application.

**Policy level:** Bans on single-use agricultural plastics. Extended producer responsibility (EPR). Increased research funding. Public awareness campaigns (Xu et al., 2020).

**Individual level:** Buy organic produce. Reduce household plastic consumption. Recycle properly. Support pro-environmental policies (Wang et al., 2020).

#### 9. Conclusion

Microplastic pollution is a complex threat to food production, soil ecosystem stability, and human health. Through physical, chemical, and biological pathways, microplastics progressively reduce soil fertility, impair crop growth, and compromise productivity. Their persistence in soil lasting decades to centuries means that contamination happening today will affect future generations. However, soil ecosystems possess remarkable regenerative capacity. If microplastic inputs are eliminated, earthworm populations can recover, microbial



communities can re-establish, and soil fertility can be gradually restored. Immediate, coordinated action by farmers, policymakers, industry, and citizens is required. Healthy soil is the foundation of healthy food, healthy people, and a healthy planet.

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# Clinical Presentation and Management of Contagious Ecthyma in a Goat

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Contagious ecthyma, commonly known as Orf or sore mouth, is a highly contagious viral disease of goats and sheep caused by a *Parapoxvirus*. The disease primarily affects the lips, oral mucosa, muzzle, and occasionally teats and feet, leading to painful proliferative and crusting lesions. Although mortality is generally low, severe outbreaks may result in marked economic losses due to reduced feeding, poor weight gain, secondary bacterial infections and mortality in young kids (Nandi *et al.*, 2011). The disease also possesses zoonotic importance, posing a risk to farmers, veterinarians and animal handlers. This article highlights the clinical features, epidemiology, diagnosis, treatment and preventive measures of contagious ecthyma in goats, supported by field observations from a naturally occurring severe case.

## Etiology

Contagious ecthyma is caused by a DNA virus belonging to:

- Family: *Poxviridae*
- Genus: *Parapoxvirus*

The virus enters the body through abrasions or damaged skin. Minor trauma caused by rough grazing materials, thorny plants, or erupting teeth commonly predisposes goats to infection (Constable *et al.*, 2017).

## Pathogenesis

The virus enters through minor abrasions in the skin or mucous membranes and replicates within epidermal keratinocytes. Viral replication causes epidermal hyperplasia and ballooning degeneration of epithelial cells, leading to the formation of papules, vesicles and pustules. These lesions subsequently rupture and become covered by thick

scabs, resulting in the characteristic proliferative crusting lesions of contagious ecthyma.

The major pathological changes include:

1. Epidermal hyperplasia
2. Ballooning degeneration
3. Vesicle and pustule formation
4. Scab formation
5. Proliferative crusting lesions

Histopathologically, lesions are characterized by:

- Hyperkeratosis
- Acanthosis
- Ballooning degeneration of keratinocytes
- Intracytoplasmic inclusion bodies (Haig and Mercer, 1998)



### Clinical Findings

The incubation period usually ranges from 3 to 7 days.

Initial lesions appear as:

- Papules, Vesicles
- Pustules

These progress into thick crusting proliferative lesions.



**Fig. 1.** Goat with contagious ecthyma (Orf) showing proliferative, ulcerative and crusting lesions of the lips and oral commissure with extensive scab formation.



**Fig. 2.** Contagious ecthyma lesions on the muzzle and lower lip of an affected goat.

### Diagnosis

Diagnosis of contagious ecthyma is often based on the presence of characteristic proliferative and crusting lesions around the lips, muzzle, and oral commissures, along with flock history and the rapid spread of disease among young animals. In many field cases, the typical clinical appearance is sufficient for a presumptive diagnosis.

Laboratory confirmation may involve:

- Polymerase chain reaction (PCR)
- Electron microscopy
- Histopathology
- Virus isolation

Histopathological examination may reveal epidermal hyperplasia, hyperkeratosis, and intracytoplasmic

inclusion bodies characteristic of parapoxvirus infection. Among the available diagnostic methods, PCR remains one of the most sensitive and reliable techniques for confirming contagious ecthyma (Hosamani *et al.*, 2009).

### Therapeutic Management

As no specific antiviral therapy is available for contagious ecthyma, treatment was directed toward controlling secondary bacterial infection, reducing inflammation, and improving feed intake.

1. **Oxytetracycline LA @ 20 mg/kg BW, IM**, repeated after 72 h, to control secondary bacterial infection.
2. **Meloxicam @ 0.5 mg/kg BW, SC/IM**, once daily for 3–5 days, to reduce pain and inflammation.
3. **Chlorpheniramine maleate @ 0.5 mg/kg BW, IM**, once daily for 3 days, as an antihistamine to alleviate irritation and discomfort.
4. Lesions were cleaned daily with **povidone-iodine solution** followed by the application of a **topical antibiotic spray/ointment**.
5. **Oral semisolid and soft feed** such as gruel, green fodder, and softened concentrate mixture was provided to facilitate feeding and prevent further trauma to oral lesions.
6. Adequate hydration, nutritional supplementation, and isolation of the affected animal were maintained throughout the treatment period.

With supportive care and proper wound management, progressive drying of scabs and healing of lesions were observed within 2–3 weeks, consistent with previous reports on the management of contagious ecthyma.





## Prevention and Control

Preventive strategies remain the cornerstone of disease control.

### Important measures include:

- Vaccination in endemic regions
- Quarantine of newly introduced animals
- Proper sanitation
- Avoidance of overcrowding
- Disinfection of feeding utensils
- Reduction of traumatic grazing injuries

Because the virus survives for long periods in dried scabs, environmental hygiene is critical for outbreak prevention (Constable *et al.*, 2017).

## Conclusion

Contagious ecthyma remains an important viral disease affecting goat health and productivity worldwide. The disease is often overlooked despite its significant economic and zoonotic implications. Severe proliferative lesions can markedly impair feeding and welfare, particularly in young kids.

The field case presented in this article emphasizes the destructive potential of advanced orf lesions when secondary bacterial infections complicate the disease process. Early diagnosis, proper supportive therapy, and preventive management are essential to reduce economic losses

and improve animal welfare in goat production systems.

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# Climate-smart agriculture: sustainable solutions for future farming

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Climate-smart agriculture (CSA) is an approach for sustainable development in agriculture to support food security under the new realities of climate change. Climate change through rainfall and temperature patterns threaten agricultural production and increase farming sustainability and biodiversity. The purpose of this article is to elaborate on the concept of CSA and demonstrate its potential.

## Introduction

Climate smart agriculture (CSA) is a holistic approach that focuses on effectively adapting agricultural methods, livestock management, forestry practices, fisheries, and crop production to mitigate the impacts of climate change. Its primary objective is to reduce greenhouse gas emissions originating from agriculture while simultaneously promoting sustainable agricultural development to ensure long-term food security. By integrating these strategies, CSA aims to enhance the resilience and adaptive capacity of agricultural systems in the face of a changing climate. CSA considers the different actions to fight the future challenges for crops and plants. In the context of increasing temperature and heat stress, CSA recommends various measures, including the use of heat-tolerant varieties, mulching, efficient water management, shade houses, boundary trees, and appropriate livestock management. Agriculture is a significant contributor to climate change, as it accounts for approximately 19-29% of total greenhouse gas (GHG) emissions. CSA guides efforts to transform agri-food systems towards environment friendly and climate-resilient practices. It supports sustainable production, improved nutrition, a healthy environment, and inclusive livelihoods. CSA is grounded in local socio-economic, environmental, and climate considerations. The FAO recommends five actions to

establish CSA: expanding the evidence base, supporting policy frameworks, strengthening institutions, increasing funding options, and implementing CSA approaches at the farm level.

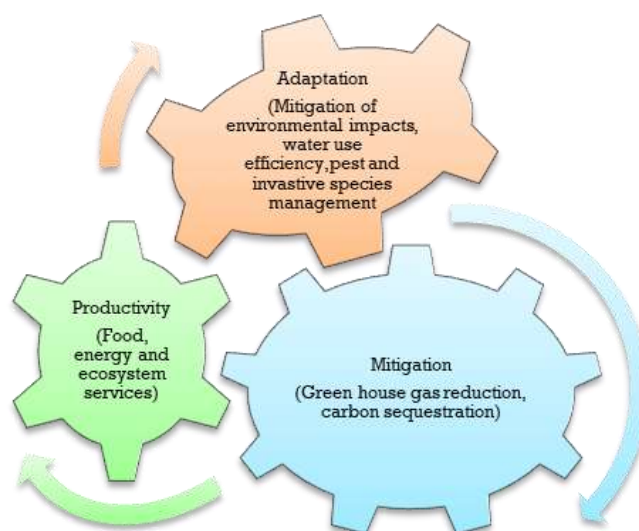


Figure 1. Concept of Climate Smart Agriculture

## Three core objectives of Climate Smart Agriculture

- Enhanced productivity:** By producing more nutritious food, CSA aims to improve food security and boost incomes, particularly for the 75% of the world's rural population who rely on agriculture for their livelihoods.



2. **Increased resilience:** CSA endeavors to reduce vulnerability to climate-related risks such as drought, pests, diseases, and disturbances. It also aims to enhance the capacity to adapt and thrive amidst long-term stresses like unpredictable weather patterns.
3. **Decreased greenhouse gas emissions:** CSA promotes low-emission practices by striving for reduced emissions per unit of food produced, preventing deforestation resulting from agriculture, and implementing methods that actively remove carbon from the atmosphere.

### Characteristics of Climate Smart Agriculture

CSA stands out from conventional agriculture due to its distinct features that prioritize reducing greenhouse gas emissions and promoting sustainable and eco-friendly farming systems. Here are some key characteristics of CSA:

**Resilience:** Building resilience in farming systems to cope with climate change, enabling them to recover from disturbances and stresses.

**Sustainable intensification:** Increasing agricultural productivity while minimizing environmental impacts through efficient and sustainable practices.

**Adaptation:** Adapting to changing climate conditions through resilient crop varieties, improved water management, and diversified farming systems.

**Mitigation:** Reducing greenhouse gas emissions from agriculture through carbon sequestration, efficient resource use, and minimizing energy consumption.

**Biodiversity conservation:** Promoting on-farm biodiversity to enhance system resilience and sustainability.

**Water management:** Efficiently managing water resources through techniques like rainwater harvesting and precision irrigation.

**Soil health and conservation:** Improving soil health, preventing erosion, and enhancing fertility and preventing land degradation.

**Economic viability and social equity:** Enhancing the economic viability of farming, improving livelihoods, and promoting equity, particularly for marginalized communities.

### Climate Smart Agriculture classification:

The classification of CSA typically considers local conditions, available resources, and the specific challenges faced by farmers in different regions.

**Table 1: Classification of Climate Smart Agriculture.**

| S. No. | CSA types                      | Practices                                                                                                                                                        |
|--------|--------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| 1.     | Water-smart CSA                | Water harvesting and water management, community management of water, solar pumps                                                                                |
| 2      | Weather-smart CSA              | Weather warning systems, agro-advisors, weather insurance                                                                                                        |
| 3.     | Seed/breed-smart CSA           | High-yielding and stress-tolerant varieties, seed banks                                                                                                          |
| 4.     | Carbon/nutrient smart CSA      | Composting, cover cropping, conservation agriculture, efficient fertiliser usage, no-till or minimum tillage, livestock and fisheries and aquaculture management |
| 5.     | Institutional/market-smart CSA | Financial services, market information, off-farm risk management, gender strategies, cross-sector linking.                                                       |

### Actions required in implementing a CSA approach.

Implementing a CSA approach involves several key actions depending on the specific context and objectives.

1. **Expanding the evidence base:** The evidence base for CSA involves assessing the impacts of climate change on agriculture, identifying vulnerabilities,



and exploring adaptation options. It also considers potential greenhouse gas emission reductions, sustainability of production systems, and necessary policy and institutional responses.

2. **Supporting enabling policy frameworks:** The approach helps formulation of relevant policies, plans, investments and coordination across processes and institutions responsible for agriculture, climate changes and food security.
3. **Managing finance options:** Established to be a financial management system to handle membership fees, farmer payments, and program expenses. The setting up of a shared bank account or the utilization of a software platform to track financial transactions and ensure transparency is to be considered. Currently, new climate financing instruments such as the green climate fund are being developed as potential avenues for sustainable development.
4. **Engaging the community:** Events, farm visits, and workshops are to be organized to engage CSA members and the broader community. A sense of connection and involvement is fostered by inviting members to volunteer on the farms, participate in harvest festivals, and contribute their skills to the CSA program.
5. **Implementing practices at field level:** CSA must be related to local farmers knowledge, needs and priorities. Local projects and institutions are to be roped in to convince the farmers to look for alternate smart farming options in view of climate change, especially rainfall pattern.

Implementing CSA requires a collaborative approach involving farmers, communities, government agencies, NGOs, research institutions, and other relevant stakeholders. Continuous learning, adaptation, and feedback mechanisms are essential for successfully implementing and scaling climate-smart agriculture practices.

## Climate-smart Agriculture Intervention

Climate-smart agricultural approaches involve land, soil, water, and biodiversity management. Interventions are those which are used to promote new or improved climate-smart agricultural approaches. These interventions can be classified based on their objectives and strategies.

1. Knowledge dissemination and ‘capacity-building’ approaches.
2. Financial approaches, like credit and subsidies including
  - a-insurance against loss
  - b-risk management strategies
3. Institutional approaches promoting participation in natural resource management committees, budgeting and gender- responsive planning.

## Conclusion

Climate smart agriculture is a new approach launched in 2009 aimed at adapting to changed agricultural practices including crop calendar for sustainability in agriculture and biodiversity in view of the climate change scenario. A framework to guide policy and technical interventions to combine the effects of changes, the challenges of achieving sustainable agricultural development and role in attaining food security. By adopting innovative techniques, such as precision farming, agroforestry, and efficient water management, we can enhance agricultural productivity while minimizing greenhouse gas emissions and preserving natural resources. Additionally, integrating climate information and early warning systems into farming practices can help farmers make informed decisions and adapt to changing climatic conditions. Embracing climate-smart agriculture not only benefits farmers but also contributes to mitigating climate change and achieving long-term food security and environmental sustainability.

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# Sustainable Farming Practices: Shaping the Future of the Chambal Region

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The Chambal region, spanning Rajasthan, Madhya Pradesh and Uttar Pradesh, relies heavily on agriculture, with major crops including wheat, maize, pulses, garlic, coriander and mustard. The region faces challenges such as severe soil erosion, erratic rainfall, declining fertility, water scarcity and pests, which reduce productivity and increase climate vulnerability. Sustainable farming practices, including crop diversification, organic farming, integrated nutrient management, conservation tillage, agroforestry and efficient irrigation, can enhance productivity, conserve resources and build climate resilience. Government programs, farmer training and community participation support the adoption of these practices. Sustainable agriculture is essential for securing food production, improving livelihoods and maintaining ecological balance, offering a roadmap for a resilient and productive future in the Chambal region.

## Introduction

Sustainable farming has emerged as a key strategy for ensuring long-term agricultural productivity and environmental conservation, particularly in resource-sensitive regions like the Chambal River basin of South-Eastern Rajasthan. This region, comprising districts such as Kota, Bundi and Baran, is an important agricultural hub where farming supports the livelihood of nearly 65-70% of the rural population. The Chambal river system, along with its extensive canal network, irrigates approximately 5–6 lakh hectares of land, enabling the cultivation of major crops like wheat, soybean, mustard and pulses. Despite its agricultural importance, the Chambal region faces increasing challenges due to intensive farming, overuse of chemical fertilizers, declining soil fertility and uneven water availability. The average annual rainfall of 700-900 mm is often erratic, making agriculture vulnerable to climate variability. While canal irrigation has improved productivity in some areas, a large number of farmers still depend on rainfall and groundwater resources, which are under continuous stress.

In this scenario, sustainable farming practices play a crucial role in shaping the future of agriculture in the Chambal region. By integrating traditional knowledge with modern scientific approaches, sustainable farming not only enhances productivity but also ensures ecological balance and long-term livelihood security for farmers. Therefore, adopting sustainable farming practices is not just an option but a necessity for transforming the Chambal region into a resilient and environmentally sustainable agricultural system.

## What is sustainable farming?

Sustainable farming is an agricultural approach that aims to **produce crops and livestock in ways that are environmentally sound, economically viable and socially responsible**, ensuring long-term productivity without degrading natural resources. It focuses on conserving soil, water and biodiversity while supporting farmers' livelihoods.



## Challenges in Chambal Region

- The Chambal region faces declining groundwater levels due to excessive irrigation withdrawal and low recharge, along with uneven canal water distribution that creates disparity among farmers and limits reliable irrigation access.
- One of the most serious problems faced by farmers in the Chambal region is severe soil erosion, which has led to extensive formation of deep gullies and ravines locally known as *beehad*. Continuous water erosion by the Chambal River system has degraded large fertile land into unproductive wastelands, resulting in loss of topsoil, reduced cultivable area, and declining soil fertility. This has significantly limited agricultural productivity and poses a major threat to sustainable farming in the region.
- Declining soil health due to low organic matter, excessive and imbalanced use of fertilizers and pesticides, leading to soil toxicity and long-term soil degradation.
- Inefficient irrigation practices with low water use efficiency, combined with climate change impacts such as irregular rainfall, droughts, and heat waves, lead to severe water Stress. As a result, frequent crop failures discourage farmers from adopting improved technologies and sustainable farming practices.
- Increasing cost of cultivation, including seeds, fertilizers, pesticides, diesel, and electricity, along with unstable agricultural productivity, significantly reduces net farm income. This situation is further worsened by limited adoption of sustainable agriculture due to fragmented landholdings, lack of awareness and technical knowledge, weak extension services and high initial investment requirements.



## Need for Sustainable Farming in Chambal Region

Sustainable farming practices are essential for the Chambal region to address the challenges mentioned above. Sustainable farming can help:

- Conservation of water resources is essential in Chambal region, where water scarcity and declining groundwater levels require efficient practices for long-term sustainability.
- Improvement of soil health is necessary due to soil degradation caused by continuous cropping and excessive chemical use; sustainable practices like organic manuring and crop rotation help restore fertility and soil structure.
- Enhancing agricultural productivity and income stability by improving resource use efficiency, maintaining soil and water quality and ensure long-term yield sustainability.
- Climate change adaptation and mitigation are crucial as sustainable farming increases resilience against droughts, heat stress and irregular rainfall patterns.
- Reduction in chemical dependency and promotion of efficient resource utilization and environmental conservation, ensuring biodiversity protection, food security and long-term agricultural sustainability.



## Sustainable Farming Practices in Chambal Region

Several sustainable farming practices can be adopted in the Chambal region, including:

### 1. Micro-Irrigation Techniques (Drip and Sprinkler Irrigation)

In the Chambal River region, efficient water use is essential due to declining groundwater levels. Micro-irrigation methods like drip and sprinkler systems deliver water directly to plant roots, reducing wastage and improving water use efficiency.

### 2. Rainwater Harvesting

Construction of farm ponds, check dams and water storage structures helps in capturing rainwater. This stored water can be used during dry periods, reducing dependence on groundwater and erratic rainfall.

### 3. Organic Farming and Use of Natural Inputs

The use of farmyard manure (FYM), compost, green manure and biofertilizers improves soil fertility and reduces dependency on chemical fertilizers. It also enhances soil microbial activity and long-term productivity.

### 4. Mulching and Crop Residue Management

Applying crop residues or organic mulch on the soil surface helps conserve moisture, regulate soil temperature and reduce soil erosion. It also adds organic matter to the soil.

### 5. Crop Diversification and Intercropping

Growing different crops and adopting intercropping systems (e.g., pulses with cereals) improves soil fertility, reduces pest incidence and minimizes the risk of crop failure.

### 6. Conservation Agriculture (Minimum/No Tillage)

Practices like minimum tillage or no-till farming reduce soil disturbance, conserve soil moisture and improve soil organic carbon, leading to better soil health over time.

### 7. Integrated Farming Systems (IFS) and Use of Improved Climate-Resilient Varieties

Combining crop production with livestock, poultry, or agroforestry ensures efficient resource utilization, improves biodiversity and provides multiple sources of income to farmers and Adopting drought-tolerant and high-yielding crop varieties helps farmers cope with climate variability and ensures stable production.

### 8. Integrated Nutrient and Pest Management (INM & IPM)

Balanced use of organic and inorganic fertilizers (INM) and eco-friendly pest control methods (IPM) reduce environmental impact while maintaining crop health and productivity.

### Government Initiatives and Support

The government has launched several initiatives to promote sustainable farming in the Chambal region, including:



- 1. Irrigation and Water Management (PMKSY & Rajasthan Initiatives)** Pradhan Mantri Krishi Sinchayee Yojana along with Rajasthan state policies promotes irrigation development (“Har Khet Ko Pani”) and efficient water use (“Per Drop More Crop”) through micro-irrigation systems like drip and sprinkler, especially in regions like Chambal.
- 2. Sustainable and Climate-Resilient Agriculture (NMSA & RAD)** National Mission on Sustainable Agriculture and Rainfed Area Development encourage climate-resilient practices, soil and water conservation, and integrated farming systems (crop + livestock + horticulture) in rainfed areas.
- 3. Promotion of Organic Farming (PKVY & State Support)** Paramparagat Krishi Vikas Yojana, supported by Rajasthan policies, promotes organic farming through use of natural inputs, reducing chemical dependency and improving soil health and sustainability.
- 4. Soil Health Management (Soil Health Card Scheme)** This scheme provides soil testing reports and nutrient recommendations to farmers for balanced fertilizer application and long-term soil fertility improvement
- 5. Farmer Support and Risk Management (PMFBY & PM-KISAN)** Pradhan Mantri Fasal Bima Yojana offers insurance against crop losses due to natural calamities, while PM-Kisan Samman Nidhi provides direct income support to farmers for agricultural inputs and improved practices.

#### **Chambal fertilisers and chemicals Ltd. Initiative and support for promoting sustainable agriculture in Chambal regions:**

Chambal is committed to balance the goal of creating sustainable wealth with the aim of enriching the environment. Accordingly, it has taken various

initiatives and implemented environment protection programmes such as ground water recharging through rainwater harvesting, energy conservation and co-generation, pollution control, Chambal green programme, green energy use and waste re-cycling.

#### **1. Uttam Bandhan Programme**

The key driver of Chambal's vision is **Uttam Bandhan**- a pioneering agriculture development and community welfare programme, initiated in partnership with farmers. The basic premise of this programme is that agricultural productivity and incomes are inextricably linked to the fertility of farm land. The main thrust of Uttam Bandhan is revitalization and restoration of cultivable land. It is one of the largest technology-based interventions for promoting and managing soil health in rural India by a private sector fertilizer company in India.

Under this programme, farmers are using various contact points to access information on scientific farming practices, learn about latest, high quality agri-inputs, locate authorized dealers, get the latest local weather forecast and know about non-farm businesses. Most significantly, it is empowering farmers to cope with problems like nutrient-deficient soils, low water tables and indiscriminate use of fertilisers and pesticides.

#### **2. Uttam Pranaam Programme:**

The initiative “**Uttam Pranaam**”, introduced by **TERI (The Energy and Resources Institute)** in collaboration with Chambal Fertilisers and Chemicals Limited, is a significant step towards promoting sustainable farming practices in India.

This program aims to improve soil health, enhance nutrient use efficiency, and encourage balanced fertilizer application among farmers. By integrating scientific knowledge with field-level advisory support, the initiative seeks to promote environmentally sustainable and economically viable





agriculture, ultimately contributing to increased productivity and long-term farm sustainability.

### Recommendations

**Awareness and Capacity Building:** Conduct workshops, training programs and demonstrations to educate farmers about sustainable farming practices.

**Incentives and Support:** Provide financial incentives, subsidies and other forms of support to encourage farmers to adopt sustainable farming practices.

**Market Linkages:** Establish market linkages and facilitate access to fair prices for sustainable produce.

**Research and Development:** Conduct research on sustainable farming practices and develop technologies that are suitable for the Chambal region.

### Conclusion

Sustainable farming is highly essential for the Chambal region to overcome critical challenges such as water scarcity, severe soil degradation and low agricultural productivity. Adoption of sustainable practices like drip irrigation, organic farming and crop diversification can significantly improve soil health, enhance water-use efficiency and stabilize crop yields in the region. Along with farmers' efforts, strong institutional support, policy incentives and effective extension services from the government are crucial to promote sustainable agriculture and ensure long-term livelihood security and environmental sustainability.

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# Good Bye to Pmos-A Plant Base Diet Therapy

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Poly-endocrine metabolic ovarian syndrome (PMOS), previously named polycystic ovary syndrome (PCOS), affects one in eight women. It is among the most common endocrine disorders affecting women of reproductive age, usually between 18 and 44 years old. It is a major contributor to subfertility, mainly because ovulatory dysfunction occurs in about 70% of those impacted. The syndrome interferes with normal ovarian activity, frequently because of multiple small cysts, resulting in hormonal imbalances and inconsistent or absent ovulation. PMOS is a persistent and complex condition with a broad spectrum of symptoms. These can include weight gain, elevated blood pressure, insulin resistance or type 2 diabetes, oily skin or dandruff, darkened skin patches (acanthosis nigricans), typically on the neck and underarms), ongoing pelvic pain, and acne. High androgen levels are characteristic of PMOS, causing hirsutism, thinning scalp hair, male-pattern baldness, and acne. Reproductive effects include irregular menstrual cycles, rare or missing ovulation, abnormal uterine bleeding, and immature ovarian follicles.

Epidemiological studies indicate that, based on NIH diagnostic criteria, 4–10% of women of reproductive age worldwide may have PMOS. The World Health Organization estimates that 613% of women worldwide who are of reproductive age have PCOS. In India, the prevalence is notably higher, with some estimates indicating that 1 in every 5 women is affected. A national survey in 2020 found that about 16% of Indian women aged 20 to 29 were diagnosed with PCOS. Although symptoms can develop soon after menarche, most diagnoses are made between ages 20 and 30. Recent studies suggest PCOS may begin during fetal development, challenging the belief that it only develops in adulthood.

In recent years, plant-based methods have gained attention as supportive options for managing PCOS, thanks to their naturally occurring bioactive compounds and fewer side effects. This review explores the latest research on how plant-based diets, herbal treatments, and phytochemicals can impact central aspects of PMOS, such as insulin resistance,

hormone imbalance, inflammation, and oxidative stress. Evidence indicates that specific plant foods and herbs could help normalize menstrual cycles, enhance metabolic health, and lower androgen levels. Overall, plant-based strategies present a promising and comprehensive way to support women dealing with PMOS

Some plant based foods that can help in reversing PMOS

## 1. Seeds of fenugreek

Soluble fiber included in fenugreek seeds slows down the absorption of carbohydrates and lessens blood sugar rises. 4-hydroxyisoleucine, the active ingredient, lowers insulin resistance in PMOS patients by increasing insulin sensitivity. This encourages ovulation and helps avoid overproduction of testosterone. These seeds high fiber content helps regulate hunger, avoid overindulging, and support weight loss initiatives. It also aid in controlling lipid



metabolism, which lowers bad cholesterol and encourages a healthier weight. One of the main reasons why women with PCOS become infertile is irregular ovulation. It is thought that fenugreek seeds encourage regular ovulation and boost ovarian function. Fenugreek extract increases the likelihood of pregnancy and improves menstrual regularity in women. Chronic inflammation is another factor that contributes to PMOS symptoms. Strong antioxidant and anti-inflammatory qualities found in fenugreek seeds aid in lowering the body's oxidative stress. Fenugreek may help with PMOS-related problems like fatigue, acne, and metabolic dysfunction by reducing inflammation.

## 2. Cinamon

Cinnamon improves lipid profiles, increases antioxidant levels, and improves menstrual regularity. Cinnamon includes substances that resemble insulin and raise the sensitivity of insulin receptors, which may help cells react to insulin more effectively. It helps in decreasing blood sugar, research suggests that cinnamon may enhance glucose tolerance and lower fasting blood glucose. Anti-inflammatory qualities of cinamon has potent anti-inflammatory substances. It also regulate menstrual cycle, according to some research, cinnamon may assist people with PMOS manage their menstrual periods. Because of these qualities, cinnamon is a compelling natural choice for women who want to add to their PCOS treatment regimen.

## 3. Green tea

Pigallocatechin gallate, a potent substance found in green tea, specifically targets insulin resistance. this substance functions by triggering enzymes that improve the way your cells use glucose. your body produces less insulin when your cells grow more sensitive to it. as a result, hormonal balance improves and pmos symptoms start to subside. Green tea inhibits the enzyme that changes androgens into estrogen by acting as a

natural aromatase inhibitor by limiting the overproduction of estrogen, this action aids in the regulation of your hormone levels. Green tea's polyphenols also lessen inflammation in your ovaries and other reproductive organs. Your ovaries can create healthier egg cells and function more normally when there is less inflammation. Regular green tea drinkers have lower levels of luteinizing hormone, which is frequently increased in pcos, according to studies. Improved fertility and more regular menstrual cycles may result from this hormone modulation by promoting thermogenesis the process by which your body burns calories to produce heat. Green tea increases your metabolism. Green tea's caffeine and catechin content can boost fat burning by as much as 17%. hence, can particularly benefit from this metabolic boost. Additionally, green tea aids in the reduction of belly fat, which is especially difficult for PMOS affected women. Green tea's antioxidants promote healthy liver function, which is essential for hormone processing and blood sugar regulation. Improved metabolic health and more effective hormone clearance follow from better liver function.

## 4. Flaxseed

Lignans, phytoestrogens plant chemicals that may have a slight estrogen-modulating effect are abundant in flaxseeds. Both soluble fiber and omega-3 fatty acids, which are known to lessen blood sugar rises and enhance insulin sensitivity, are found in flaxseeds. Soluble and insoluble fiber, which promotes gut health and regular bowel motions, is abundant in flaxseeds. Because flaxseed contains a lot of lignans, which are phytoestrogens that can help regulate hormone metabolism, it may help lower testosterone levels and improve menstrual regularity. Its omega-3 fatty acids are also believed to enhance insulin sensitivity and lessen inflammation. Flaxseed's soluble fiber can help with weight control and glucose metabolism.



## 5. Turmeric

The most uncomfortable PCOS symptoms, including headaches, bloating, cramps, weight gain, exhaustion, food intolerances, and inflammation, are believed to be caused by chronic, low-grade inflammation. Additionally, increased insulin resistance, excess androgens (high testosterone levels), and more severe PCOS symptoms are all caused by inflammation. The potent anti-inflammatory and antioxidant qualities of turmeric's curcumin are thought to rival those of ibuprofen and aspirin.

## 6. Papaya

PCOS symptoms, which frequently involve inflammation, may be lessened by papaya. Papaya is good for women with PMOS who have digestive problems since it contains the enzyme papain, which helps with digestion. Papaya consumption might enhance digestion and alleviate symptoms like constipation and bloating. For the immune system, Vitamins A and E are naturally found in papaya and are vital for a strong immune system. Because PMOS can impair immunity, it is especially crucial for women to strengthen their immune systems. Hormonal equilibrium may be supported by the vitamins and antioxidants found in papaya. Hormonal imbalances are a hallmark of PMOS, and eating papaya may help control these imbalances. Antioxidants and enzymes found in papaya support healthy skin. Skin conditions like acne and excessive oiliness are common in women with PMOS. Including papaya in the diet might lessen these symptoms and enhance skin health. By lowering cholesterol and halting oxidative damage, papaya's fiber and antioxidants support heart health. Papaya is an important component of a heart-healthy diet because PMOS is linked to a higher risk of cardiovascular issues.

## 7. Pineapple

Pineapple is a topic of interest for treating the persistent low-grade inflammation that frequently coexists with PCOS since it contains bromelain. The anti-inflammatory properties of bromelain may aid in lowering systemic inflammatory indicators. This enzyme can support a reduced inflammatory burden in the body by modulating inflammatory pathways. Additionally, the fruit's composition directly affects metabolic function, especially in relation to insulin resistance, a feature of PMOS. By reducing the pace at which glucose enters the bloodstream, the fiber content helps lessen the glycemic effect of the fruit's natural sugars. The quick insulin spikes that can exacerbate insulin resistance are lessened by this longer release. According to research, bromelain may also help alleviate metabolic and endocrine disorders, such as lowering tumor necrosis factor alpha (TNF $\alpha$ ), a crucial inflammatory marker associated with PCOS pathogenesis. Additionally, because of its antioxidant qualities, which are advantageous for collagen formation and ovarian health, the high vitamin C concentration improves overall endocrine function.

## 8. Pumpkin seed

It's possible that pumpkin seeds will lessen these symptoms. They include beta-sitosterol, which can help lower cholesterol and lessen hair loss by blocking the enzyme that changes testosterone into DHT. Our bodies require essential fatty acids (EFAs), which are also found in pumpkin seeds. These EFAs lower insulin levels, balance blood sugar, enhance hair, skin, and nails, assist control periods, and regulate hormone activity. For women with PMOS, pumpkin seeds are therefore a superfood. Your body requires magnesium for energy, heart health, bone and dental health, and healthy bowel movements, even though you may not give it much thought. Almost half of your daily magnesium needs can be found in one quarter cup of these





seeds. Unbelievably, pumpkin seeds are beneficial. They include a lot of tryptophan, which your body uses to make serotonin and melatonin, which promote sleep and lessen depression. This works very well if you have a little piece of fruit and pumpkin seeds as a snack a few hours before bed. When used during seed rotation, pumpkin seeds also aid to maintain and regulate our menstrual cycle. Eating particular seeds during the two major stage of your menstrual cycle is known as "seed rotation" or "seed cycling." Certain seeds can increase progesterone levels in the second half of the cycle and estrogen levels in the beginning.

### 9. Chia seed

Chia seeds are high in fiber, digestion is slowed and abrupt blood sugar rises avoided. This has a significant role in reducing insulin resistance, which is a major cause of PMOS. According to the Journal of Nutritional Science, these seeds are rich in antioxidants, dietary fiber, and omega-3 fatty acids, all of which aid in lowering oxidative stress and inflammation. Women with PMOS frequently have higher levels of both of these variables. Chia seeds aid in controlling weight. These tiny seeds are a potent source of fiber and protein. Thus, it lessens needless cravings and hunger pangs and makes you feel fuller for longer.

### 10. Quinoa

Quinoa helps maintain hormonal balance in a number of ways. Stable blood sugar results in stable insulin, which aids in lowering the overproduction of androgens, which are male hormones that are frequently increased in PMOS. Quinoa's magnesium helps lower testosterone levels and promote insulin

sensitivity. Quinoa's fiber aids in the digestive tract's removal of extra estrogen. Quinoa enhances the way cells react to hormones by lowering inflammation. Compared to white rice, which has 4g of protein per cup, quinoa has roughly 8g. It also has lower GI than white rice, which improves blood sugar level. Quinoa supports hormonal balance since it has higher levels of iron, zinc and magnesium than rice. Quinoa's flavonoids, such as kaempferol and quercetin, can lessen PMOS related inflammation.

### Conclusion

PMOS is a complex disorder that can worsen as a result of certain environmental and genetic variables, as well as poor dietary and lifestyle choices. Given that the majority of females with PMOS are also obese, it has been determined that obesity is associated with an increased risk of PMOS. Additionally, obesity raises the risk of insulin resistance, which in turn leads to hyperandrogenism, hirsutism, and other hormonal problems that impact the ovaries and cause them to develop cysts. Herbal and medicinal treatments may lessen PMOS symptoms, but long-term lifestyle changes are necessary to fully treat the condition. Diets high in protein, low in fat, and moderate in carbohydrates combined with an active lifestyle may be the key to significantly reducing PMOS symptoms. In order to draw firm conclusions, it is recommended that future research studies and clinical trials consider a variety of parameters, such as dietary and eating patterns, behavioral changes, herbal and supplemental treatments, and other lifestyle-related practices

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# RNAi-Based Pest Control: A New Era in Crop Protection

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For decades, protecting crops from insects has meant reaching for broad-spectrum chemistry that kills indiscriminately and loses effectiveness as pests evolve resistance. RNA interference (RNAi) offers a fundamentally different approach: instead of poisoning an insect's nervous system, it silences a single gene the pest cannot survive without. This article explains, in accessible terms, how RNAi works, how double-stranded RNA (dsRNA) can be delivered to pests through engineered plants, external sprays, or nanoparticle carriers, and how this technology moved from a laboratory curiosity into a commercial reality with the 2024 approval of the first sprayable RNAi biopesticide for Colorado potato beetle control. It compares RNAi against conventional chemical insecticides and Bt transgenic crops, reviews evidence on efficacy and specificity across insect groups, and takes a clear-eyed look at the technical and regulatory hurdles, including inconsistent dsRNA uptake across species, production cost, environmental stability, and biosafety questions, that still stand between RNAi and widespread adoption. It closes with a look at where the field is headed, including AI-assisted dsRNA design and improved delivery chemistry.

## 1. Introduction

Every growing season, farmers face the same basic trade-off: protect the crop from insects, or risk losing a meaningful share of the harvest to them. For most of the last century, the answer has been chemical insecticide, and it has worked, up to a point. But that point is increasingly being reached. Repeated use of the same chemical classes has driven resistance in many major pest species, while concerns about pollinator health, water contamination, and residues on food have pushed regulators and consumers alike to ask for something better (**Ahmad *et al.*, 2025**).

RNA interference offers a genuinely different kind of answer. Rather than poisoning a pest through a broad physiological attack, RNAi shuts down a single gene that the insect cannot function without, using nothing more exotic than a strand of double-stranded RNA that matches the insect's own genetic sequence (**Liu and Smagghe, 2026**). Because the silencing effect depends on a close sequence match, it can, in principle, be made specific to one pest

species while leaving beneficial insects and other wildlife untouched (**Mamta and Rajam, 2017**).

This is not a purely theoretical idea anymore. Transgenic corn engineered to produce dsRNA against the western corn rootworm has been grown commercially for several years, and in January 2024 the US Environmental Protection Agency registered the first sprayable RNAi biopesticide, targeting the Colorado potato beetle, marking a genuine turning point for the technology. This article walks through how RNAi works, how it is delivered to pests in the field, what the evidence says about its performance so far, and what stands between today's early products and a much larger role in crop protection.

## 2. The Science: How RNAi Silences a Gene

RNA interference is not a human invention; it is a natural gene-regulation mechanism found across plants, animals, and fungi, first described in the roundworm *Caenorhabditis elegans* in the late 1990s. The process is triggered when a cell encounters double-stranded RNA, a molecule that does not



normally last long inside a healthy cell and is treated as a signal that something needs to be dealt with (Székács *et al.*, 2021).

When a pest insect takes up dsRNA, whether by feeding on treated leaves, absorbing a topical spray, or eating plant tissue engineered to produce it internally, an enzyme called Dicer cuts the long dsRNA strand into short fragments known as small interfering RNAs (siRNAs). These fragments are loaded into a protein complex called RISC (RNA-induced silencing complex), which uses the siRNA as a template to find and destroy any messenger RNA (mRNA) in the cell that carries a matching sequence. If that mRNA happens to code for a protein the insect needs to survive, grow, or reproduce, silencing it can be lethal or severely disabling. Figure 1 summarizes this five-step chain of events.

Because the silencing effect depends on matching a specific genetic sequence rather than a general toxic mechanism, RNAi-based products can in principle be designed to affect only the target pest species, sparing pollinators, natural enemies, and other non-target organisms (Fan *et al.*, 2026

### 3. Getting dsRNA Into the Pest: Delivery Platforms

A gene-silencing molecule is only useful if it can reliably reach the pest in a form, it will actually take up. Researchers have developed several distinct routes for delivering dsRNA in the field, each with its own trade-offs in cost, durability, and regulatory pathway (Das and Sherif, 2020). Table 1 summarizes how these routes compare with the two dominant conventional approaches: chemical insecticides and Bt transgenic crops.

**Table 1. How RNAi-based control compares with conventional pest control approaches**

| Feature                   | Chemical Insecticides                       | Bt Transgenic Crops                | RNAi-Based Control                                                |
|---------------------------|---------------------------------------------|------------------------------------|-------------------------------------------------------------------|
| Mode of action            | Disrupts nerve/muscle or metabolic function | Toxin protein disrupts gut cells   | Silences a specific essential gene                                |
| Target specificity        | Broad; often affects non-target insects     | Narrow, protein-dependent          | Very narrow, sequence-dependent                                   |
| Resistance risk           | High; widespread resistance documented      | Moderate; some resistance reported | Present but potentially manageable by re-targeting                |
| Effect on beneficials     | Frequently harmful                          | Generally low                      | Minimal when sequence is pest-specific                            |
| Environmental persistence | Variable; some residues persist             | Low, expressed in planta           | Low; dsRNA degrades quickly in soil/water                         |
| Application route         | Spray, soil drench, seed treatment          | Built into the plant genome        | Spray (SIGS), seed/plant expression (HIGS), or microbial delivery |



### 3.1 Host-Induced Gene Silencing (HIGS)

In this approach, the crop plant itself is genetically engineered to produce dsRNA against a pest gene. When the insect feeds on the plant, it ingests the dsRNA along with its meal, triggering silencing from the inside. This is the strategy behind the RNAi trait added to some commercial corn varieties to protect against corn rootworm, a pest that had developed resistance to several Bt toxins.

### 3.2 Spray-Induced Gene Silencing (SIGS)

SIGS avoids genetic modification of the crop altogether. Instead, dsRNA is manufactured externally, formulated much like a conventional biopesticide, and sprayed directly onto plant surfaces. The pest picks up the dsRNA by feeding on treated foliage. This is the approach behind ledprona, the active ingredient in the product Calantha, which became the first sprayable dsRNA pesticide approved anywhere in the world when the EPA registered it in January 2024 for control of the Colorado potato beetle, at an application rate as low as four grams of active ingredient per acre (Rodrigues *et al.*, 2021).



Figure 1: Spray-induced gene silencing (SIGS) delivers double-stranded RNA directly onto crop foliage, enabling targeted pest control

### 3.3 Nanoparticle-Encapsulated dsRNA

Naked dsRNA breaks down quickly in sunlight, soil, and water, which limits how long a spray application stays effective. Wrapping dsRNA in nanoscale carriers, built from materials such as clay particles, lipids, or biodegradable polymers, can shield it from degradation and improve how efficiently it is taken

up by pest cells, extending the practical window in which a treatment remains active in the field.

### 3.4 Microbial and Symbiont-Based Expression

A less mature but promising route uses engineered bacteria or yeast to manufacture dsRNA, which is then introduced into a pest's feeding environment or gut microbiome. This approach is still largely confined to research settings but could eventually offer a low-cost production and delivery pathway for certain gut-feeding insects.

## 4. From Lab Bench to Farm Field: Key Milestones

RNAi-based pest control did not appear overnight. It followed a fairly typical path for a biotechnology: basic discovery, years of proof-of-concept research in insects, a first commercial transgenic trait, and finally regulatory approval of a standalone sprayable product. Figure 2 traces that path.



Figure 2: Key milestones in the development of RNAi-based pest control, from initial discovery to commercial deployment (Mendoza-Alatorre *et al.*, 2025)

The 2024 registration of Calantha was a genuine watershed moment: after more than four years of EPA review and over 200 field trials, it became the first foliar-applied RNA product ever registered under the Federal Insecticide, Fungicide, and Rodenticide Act, and the industry's Insecticide Resistance Action





Committee created an entirely new mode-of-action category, Group 35, to classify it (**Rodrigues et al., 2021**). Laboratory work characterizing the product's active ingredient found that it silences a gene coding for a proteasome subunit the beetle needs to break down proteins, with lethal effects appearing within days of exposure at very low concentrations (**Rodrigues et al., 2021**).

## 5. What the Evidence Shows

Across more than 30 pest species studied to date, most belonging to the insect orders Lepidoptera (moths and butterflies), Hemiptera (true bugs), and Coleoptera (beetles), RNAi has demonstrated the ability to significantly reduce survival and reproduction when dsRNA is properly targeted and delivered (**Germing et al., 2025**). Coleopteran pests such as the Colorado potato beetle and corn rootworm have generally proven to be the most responsive group, which is part of why the first commercial products have targeted beetles rather than other insect orders (**Mamta and Rajam, 2017**).

Efficacy is far from uniform across species, however. Differences in how efficiently an insect's gut absorbs dsRNA, how quickly it degrades internal double-stranded RNA, and whether the silencing signal spreads systemically throughout the body all affect how well a given RNAi treatment performs, and these factors vary widely even between closely related species (**Mamta and Rajam, 2017**). This variability is one of the central open questions the field is still working through, rather than a solved problem.

## 6. The Hurdles That Remain

For all its promise, RNAi-based pest control is still working through real technical and practical limitations. Variable efficacy across insect species remains the most fundamental scientific challenge: a treatment that works well against one beetle species may barely affect a related insect because of differences in gut chemistry, dsRNA degrading

enzymes, or how well the silencing signal spreads through the body (**Mamta and Rajam, 2017**).

Environmental stability and delivery are closely related concerns. Naked dsRNA sprayed onto a leaf can break down within hours to days under field conditions such as UV exposure and rainfall, which limits residual control and may require more frequent applications unless nanoparticle or other protective formulations are used (**Panozzo et al., 2025**). Manufacturing cost has also historically been a barrier, since producing dsRNA at commercial scale was, until recently, considerably more expensive than synthesizing conventional chemical active ingredients, although cell-free bioprocessing platforms are beginning to narrow that gap (**Das and Sherif, 2020**).

Biosafety and regulatory questions are just as important as the technical ones. Environmental groups have raised concerns about potential unintended effects on pollinators and other non-target organisms, and regulators have generally responded by granting time-limited registrations, such as the EPA's three-year window for *Calantha*, paired with a requirement to gather additional field data before renewal (**Rodrigues et al., 2021**). Broader ethical and legal debates over transgenic HIGS crops, which involve the same genetic-modification concerns as earlier GM technologies, add a further layer of complexity that sprayable SIGS products largely sidestep (**Ahmad et al., 2025**).

None of these challenges appear to be fatal to the technology, but they do mean that RNAi is likely to expand gradually, pest by pest and crop by crop, rather than replacing existing tools all at once.

## 7. Where RNAi Pest Control Is Headed

Several developments look likely to shape the next stage of this technology. Artificial intelligence is already being used to predict RNA secondary structure and silencing efficiency computationally, which can shorten the trial-and-error process of



finding an effective target sequence and speed up development of new RNAi agents (**Liu and Smagghe, 2026**). Integration with multi-omics data, combining genomic, transcriptomic, and proteomic information about a pest species, is also helping researchers identify better gene targets with fewer dead ends (**Liu and Smagghe, 2026**).

On the delivery side, continued refinement of nanoparticle carriers and other stabilizing formulations should extend how long a sprayed dsRNA treatment remains active in the field, addressing one of the technology's most immediate practical limitations (**Panozzo et al., 2025**). Researchers are also exploring RNAi applications beyond insect pests, including weed control through spray-induced gene silencing in plants, though that particular application is still in early stages and has yet to produce field-ready products (**Panozzo et al., 2025**).

## 8. Conclusion

RNA interference will not make chemical insecticides disappear, and it is not a silver bullet for every pest problem a farmer faces. What it does offer is something genuinely new: a way to disable a specific pest by name, so to speak, using nothing more than a strand of RNA matched to that pest's own genetic code. That precision is exactly what is missing from most of the tools currently available, and it is why RNAi has moved, in less than two decades, from a laboratory curiosity to a registered commercial product protecting real potato fields. The technology's next chapter will be written largely by whether researchers can close the remaining gaps around delivery stability, production cost, and consistent efficacy across pest species, and by how transparently the industry addresses legitimate questions about non-target safety. If that work continues at its current pace, RNAi looks set to become a standard, if not universal, part of the crop protection toolkit within the coming decade.

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# **Agroforestry for Sustainable Agriculture: Soil Health, Climate Resilience, Carbon Sequestration and the Traditional Bari System of Assam**

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Climate change, soil degradation, biodiversity loss and declining farm productivity have increased the need for sustainable agricultural systems. Agroforestry, the deliberate integration of trees with crops and livestock, has emerged as an effective nature-based solution for improving soil health, enhancing climate resilience, and diversifying farmers' livelihoods. This article highlights the principles and major agroforestry systems, emphasizing their role in improving soil physical, chemical and biological properties through enhanced nutrient cycling, biological nitrogen fixation and increased soil organic carbon. It also discusses the contribution of agroforestry to climate change mitigation through carbon sequestration, carbon credits and support for India's Nationally Determined Contributions (NDCs) under the Paris Agreement. The traditional Bari system of Assam is presented as an exemplary indigenous agroforestry model that integrates biodiversity conservation, household food security and sustainable resource management. The article further outlines the importance of multipurpose tree species, intercropping, emerging technologies and future opportunities for scaling up agroforestry. By integrating traditional knowledge with scientific innovation, agroforestry offers a practical pathway towards sustainable agriculture, resilient rural livelihoods and environmental conservation.

## **Introduction**

Agriculture today faces unprecedented challenges from climate change, soil degradation, biodiversity loss and declining farm profitability. Rising temperatures, erratic rainfall, recurrent floods and droughts, coupled with unsustainable land-use practices, have accelerated soil erosion, nutrient depletion, groundwater exploitation and the loss of soil biodiversity. Conventional monoculture-based farming, characterized by intensive tillage and excessive dependence on synthetic inputs, has undoubtedly enhanced food production but has also weakened the resilience and sustainability of agricultural ecosystems. These growing concerns underscore the urgent need for farming systems that simultaneously improve productivity, restore natural resources and strengthen climate resilience (FAO, 2021; IPCC, 2022).

In this context, agroforestry has emerged as a scientifically proven, nature-based solution that

integrates trees with crops and where appropriate, livestock to create productive, resilient and environmentally sustainable farming systems. By mimicking natural ecosystems, agroforestry improves soil health through enhanced nutrient cycling, biological nitrogen fixation, increased soil organic carbon and greater microbial activity, while conserving biodiversity, regulating microclimates, reducing soil erosion, improving water-use efficiency, and sequestering atmospheric carbon. These multiple ecosystem services make agroforestry a cornerstone of climate-smart agriculture and regenerative land management (Nair, 1993; Jose, 2009).

Agroforestry is particularly important in India, where nearly 86% of farmers are small and marginal landholders vulnerable to climate change and soil degradation. By integrating trees with crops and livestock, it diversifies farm income through timber, fruits, fodder, medicinal plants and other products while enhancing food security, soil health





and ecological sustainability. India reinforced its commitment by adopting the National Agroforestry Policy in 2014. In Assam, the traditional Bari system exemplifies an indigenous, multi-layered agroforestry model that efficiently integrates trees, crops, livestock and organic nutrient recycling. Scientific research now confirms the ecological benefits of such systems, highlighting their role in improving soil health, sequestering carbon, supporting India's Nationally Determined Contributions (NDCs) under the Paris Agreement, and advancing the vision of Viksit Bharat @2047 through climate-resilient and sustainable agriculture.

### Types and Practices of Agroforestry

Agroforestry is a sustainable land-use system that integrates trees with crops and where appropriate, livestock on the same land to improve productivity, resource-use efficiency and environmental sustainability. It enhances soil fertility through organic matter recycling and biological nitrogen fixation, conserves biodiversity, reduces soil erosion, improves microclimate, increases carbon sequestration, and diversifies farm income. By strengthening ecosystem stability, agroforestry also enhances resilience to climate change and supports sustainable agricultural production.

The selection of an appropriate agroforestry system depends on several factors, including climatic conditions, soil characteristics, farm size, market opportunities and the socioeconomic status of farmers. India possesses a rich diversity of agroforestry systems that have evolved through indigenous knowledge and adaptation to local agroecological conditions. These systems differ in their structure and management practices but share the common objective of promoting sustainable agriculture through efficient resource conservation, improved soil health, enhanced biodiversity, climate change mitigation and adaptation and livelihood security (Jose, 2009; Dhyani et al., 2017). Some of

the major agroforestry systems practiced in India and their key functions are presented in Table 1.

**Table 1. Major Agroforestry Systems and Their Functions**

| Agroforestry System        | Major Components                     | Major Benefits                                                 | Indian Examples                             |
|----------------------------|--------------------------------------|----------------------------------------------------------------|---------------------------------------------|
| Agrisilviculture           | Trees + Agricultural crops           | Timber, nutrient cycling, soil fertility, carbon sequestration | Poplar–wheat, Teak–paddy, Bamboo–vegetables |
| Silvopasture               | Trees + Fodder + Livestock           | Fodder security, manure recycling, soil improvement            | Rajasthan, Gujarat, Karnataka               |
| Agrosilvopasture           | Trees + Crops + Livestock            | Diversified income, climate resilience, efficient resource use | North East India, Himalayan region          |
| Alley Cropping             | Tree rows + Annual crops             | Nitrogen fixation, green manure, erosion control               | Southern India, North Eastern Hills         |
| Windbreaks & Shelterbelts  | Boundary tree plantations            | Wind protection, moisture conservation, biodiversity           | Rajasthan, Gujarat, Coastal India           |
| Home Gardens (Bari System) | Trees + Fruits + Vegetables + Spices | Food security, nutrient recycling, biodiversity                | Assam and North East India                  |



|  |           |              |  |
|--|-----------|--------------|--|
|  | Livestock | conservation |  |
|--|-----------|--------------|--|

### Importance of Multipurpose Tree Species and Intercropping in Agroforestry Systems

The success of agroforestry largely depends on the selection of suitable multipurpose tree species that complement agricultural crops while providing ecological and economic benefits. In Assam and the North Eastern Region, species such as Titachapa (*Magnolia champaca*), Mahogany (*Swietenia macrophylla*), Agar (*Aquilaria malaccensis*), Gamari (*Gmelina arborea*), Hollong (*Dipterocarpus macrocarpus*), Neem (*Azadirachta indica*) and Bamboo (*Bambusa* spp.) are well suited for agroforestry because they provide timber, agarwood, fuelwood, fodder and other non-timber forest products while improving soil fertility, biodiversity, carbon sequestration and microclimate regulation.

During the early years of plantation establishment, these trees can be successfully intercropped with ginger, turmeric, black pepper, pineapple, banana, colocasia, pulses, soybean, vegetables and medicinal plants, ensuring continuous income until trees mature. Tree litter, deep root systems and legume intercrops enhance nutrient cycling, soil organic carbon, biological nitrogen fixation and microbial activity, while continuous ground cover reduces erosion, conserves moisture and improves water infiltration. Diversified tree-crop combinations also support pollinators, mycorrhizal fungi, beneficial insects and birds, strengthening ecosystem resilience and natural pest regulation. Appropriate tree spacing, pruning and canopy management minimize competition between trees and crops, resulting in higher Land Equivalent Ratio (LER), greater productivity and improved climate resilience compared to monoculture farming.

**Table 2. Multipurpose Tree Species and Suitable Intercrops**

| Tree Species | Major Benefits                                     | Suitable Intercrops                       |
|--------------|----------------------------------------------------|-------------------------------------------|
| Titachapa    | Timber, soil conservation, nutrient cycling        | Ginger, Turmeric, Pineapple               |
| Mahogany     | High-value timber, carbon sequestration            | Pulses, Vegetables, Ginger                |
| Agar         | Agarwood, essential oil, biodiversity conservation | Ginger, Turmeric, Black pepper, Pineapple |
| Gamari       | Timber, rapid biomass production                   | Vegetables, Pulses                        |
| Neem         | Medicinal value, natural pest management           | Pulses, Vegetables                        |
| Bamboo       | Soil conservation, biomass, carbon storage         | Ginger, Turmeric, Banana                  |

### How Agroforestry Improves Soil Health

Agroforestry improves soil health by integrating trees with crops and livestock, creating a productive and self-sustaining ecosystem. The continuous addition of leaf litter, root biomass, and organic residues increases soil organic matter, which

improves soil structure, reduces bulk density, enhances porosity and increases water infiltration and moisture-holding capacity. Deep-rooted trees reduce soil compaction, recycle nutrients from deeper soil layers and their canopies minimize runoff, soil erosion and nutrient loss. Nitrogen-fixing tree



species such as *Gliricidia sepium*, *Leucaena leucocephala*, *Albizia lebbeck* and *Sesbania grandiflora* enrich the soil through biological nitrogen fixation in association with *Rhizobium* bacteria, thereby reducing the need for synthetic nitrogen fertilizers. The accumulation of soil organic carbon further enhances cation exchange capacity, nutrient retention, soil pH buffering and overall soil fertility (Brady & Weil, 2017; Lal, 2020).

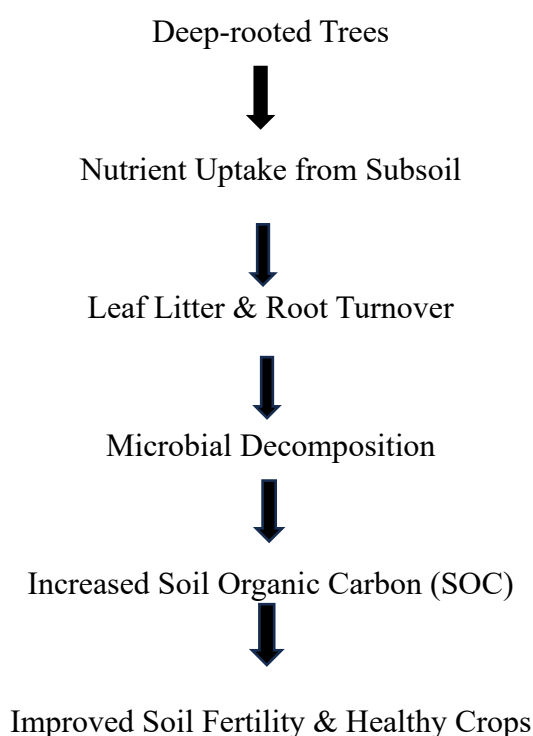
Agroforestry also enhances the biological health of soils by promoting diverse microorganisms, earthworms, fungi and beneficial insects that accelerate decomposition, nutrient cycling and humus formation. Mycorrhizal fungi associated with common agroforestry tree species such as *Titachapa* (*Magnolia champaca*), Mahogany (*Swietenia macrophylla*), Agar (*Aquilaria malaccensis*), Gamari (*Gmelina arborea*), Neem (*Azadirachta indica*), Bamboo (*Bambusa* spp.), Jackfruit (*Artocarpus heterophyllus*), Mango (*Mangifera indica*), Coconut (*Cocos nucifera*), and Arecanut (*Areca catechu*) improve the uptake of phosphorus, micronutrients and water while enhancing drought tolerance and soil aggregation. Together, these physical, chemical and biological processes restore degraded soils, improve resilience to climate change and sustain long-term agricultural productivity.

**Table 3: Major Soil Health Benefits of Agroforestry**

| Soil Property | Agroforestry Effect                                                                            | Key Benefits                                      |
|---------------|------------------------------------------------------------------------------------------------|---------------------------------------------------|
| Physical      | Improved soil structure, aggregation, porosity, infiltration, reduced bulk density and erosion | Better root growth, water storage, reduced runoff |

|            |                                                                                                   |                                                                                |
|------------|---------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------|
| Chemical   | Nutrient recycling, biological nitrogen fixation, higher soil organic carbon (SOC), increased CEC | Enhanced soil fertility, nutrient availability, reduced fertilizer requirement |
| Biological | Increased microbial diversity, earthworms, mycorrhizae and beneficial insects                     | Improved nutrient cycling, disease suppression, greater ecosystem resilience   |

### Nutrient Cycling in Agroforestry



### Assam's Traditional Bari System: Nature's Own Agroforestry Model

The Bari system (homestead agroforestry) of Assam is one of India's oldest and most ecologically efficient indigenous agroforestry systems, developed through generations of traditional knowledge. Established around rural households, it integrates



trees, fruit crops, vegetables, spices, medicinal plants, climbers, livestock, poultry and occasionally fish ponds into a compact, multi-layered production system. Designed to meet household requirements for food, fodder, fuelwood, timber, medicine and supplementary income, the Bari efficiently utilizes sunlight, water, nutrients and vertical space while minimizing dependence on external inputs. Continuous recycling of household organic waste, crop residues and livestock manure maintains soil fertility, enhances soil organic carbon and microbial activity and sustains long-term productivity. The diversified vegetation moderates the microclimate, conserves soil moisture, reduces erosion and flood damage, supports pollinators and beneficial organisms, and strengthens resilience against climatic extremes. Long before the concepts of climate-smart agriculture, regenerative farming and circular economy emerged, the Bari system embodied these principles, demonstrating how biodiversity conservation, soil restoration, nutrient recycling and livelihood security can coexist within a single sustainable farming system (Das & Das, 2005; Dhyani et al., 2017).

**Table 4. Vertical Structure of Assam's Traditional Bari System**

| Layer                       | Major Species                                       | Ecological and Economic Functions                        |
|-----------------------------|-----------------------------------------------------|----------------------------------------------------------|
| Tier I<br>(Emergent Canopy) | Coconut, Arecanut                                   | Wind protection, sunlight interception, long-term income |
| Tier II<br>(Upper Canopy)   | Jackfruit, Mango, Gamari, Titachapa, Mahogany, Agar | Timber, fruits, carbon sequestration, shade              |

|                             |                                            |                                                            |
|-----------------------------|--------------------------------------------|------------------------------------------------------------|
| Tier III<br>(Middle Canopy) | Banana, Papaya, Assam Lemon, Guava         | Household nutrition and year-round income                  |
| Tier IV<br>(Shrub Layer)    | Chilli, Coffee, Hibiscus, Medicinal plants | Spices, medicines, pollinator habitat                      |
| Tier V<br>(Ground Layer)    | Ginger, Turmeric, Colocasia, Yam           | Soil cover, moisture conservation, erosion control         |
| Climbers                    | Black Pepper                               | Efficient vertical space utilization and additional income |

### Agroforestry and Climate Resilience

Climate change, characterized by rising temperatures, erratic rainfall, droughts, floods, cyclones and land degradation, poses a significant threat to agricultural sustainability. Recognized by the IPCC as a nature-based solution, agroforestry enhances climate resilience by integrating trees with crops and livestock to create diversified and sustainable farming systems. Deep-rooted trees improve drought tolerance by accessing moisture from deeper soil layers, while increased soil organic matter, leaf litter and mulching enhance soil moisture retention, water infiltration and groundwater recharge. Tree canopies intercept rainfall and extensive root systems stabilize the soil, reducing runoff, erosion and flood risks. Windbreaks and shelterbelts protect crops from strong winds and cyclones, while the multilayered canopy moderates temperature, reduces evapotranspiration and creates favourable microclimatic conditions.

Agroforestry also conserves biodiversity by providing habitats for pollinators, birds, beneficial insects, mycorrhizal fungi, and other soil organisms,



thereby strengthening ecosystem stability and natural pest regulation. Traditional systems such as Assam's Bari (home garden) system demonstrate the role of trees in improving soil and water conservation, reducing climate-related risks, and sustaining rural livelihoods. Through carbon sequestration, biodiversity conservation, natural resource management, and income diversification, agroforestry has emerged as a key climate-smart agricultural strategy for building resilient farming systems and ensuring long-term food and livelihood security.

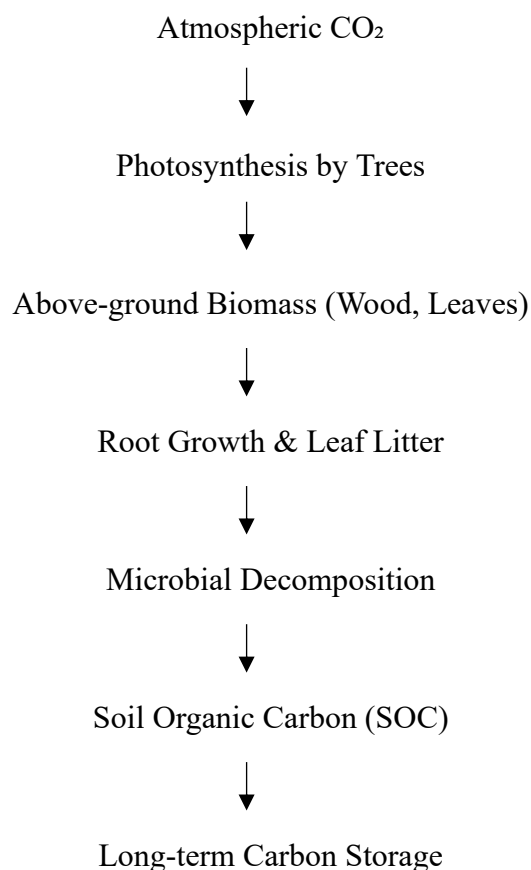
### Agroforestry, Carbon Sequestration and India's Climate Commitments

Agroforestry is one of the most effective nature-based solutions for addressing climate change while enhancing agricultural sustainability. By integrating trees with crops and livestock, agroforestry captures atmospheric carbon dioxide (CO<sub>2</sub>) through photosynthesis and stores it in above-ground biomass (trunks, branches and leaves), below-ground root systems, and soil organic carbon (SOC). Continuous additions of leaf litter, root biomass and pruning residues decompose through microbial activity, enriching SOC and improving soil fertility, nutrient cycling, soil structure, water-holding capacity and overall ecosystem productivity. Compared with annual monocropping systems, agroforestry stores substantially higher amounts of carbon while simultaneously conserving biodiversity, reducing land degradation, enhancing climate resilience and supporting sustainable land management. Thus, agroforestry functions as a long-term natural carbon sink, contributing significantly to climate change mitigation and adaptation.

The process of carbon sequestration in agroforestry begins with the absorption of atmospheric CO<sub>2</sub> by trees through photosynthesis. Carbon is subsequently stored in woody biomass, foliage and roots, while leaf litter and root residues are decomposed by soil microorganisms, leading to

the accumulation of soil organic carbon. This continuous biological cycle improves soil health, increases moisture retention, promotes beneficial microbial activity and enhances nutrient availability, thereby creating productive and resilient farming systems capable of withstanding climatic stresses such as droughts, floods and temperature extremes.

### Carbon Sequestration Process in Agroforestry



In addition to its environmental benefits, agroforestry creates new economic opportunities through carbon markets. Carbon credits are emerging as an important additional source of income for farmers adopting agroforestry and other climate-smart agricultural practices. One carbon credit represents the removal or avoidance of one metric tonne of carbon dioxide equivalent. As trees sequester carbon in biomass and soils, farmers can earn carbon credits while continuing to generate income from agricultural crops, fruits, timber, bamboo, fodder and livestock enterprises. Since





transaction costs and certification procedures are often beyond the capacity of individual smallholders, aggregation through Farmer Producer Organizations (FPOs), Farmer Producer Companies (FPCs) and cooperatives plays a crucial role in enabling participation in carbon markets. Effective implementation requires robust Measurement, Reporting and Verification (MRV) systems supported by modern technologies such as remote sensing, Geographic Information Systems (GIS), drones, artificial intelligence and digital carbon accounting platforms to ensure accurate estimation and verification of carbon sequestration.

Agroforestry is also a vital strategy for helping India achieve its Nationally Determined Contributions (NDCs) under the Paris Agreement adopted during the 21st Conference of the Parties (COP21) to the United Nations Framework Convention on Climate Change (UNFCCC) in 2015. The Paris Agreement seeks to limit the rise in global average temperature to well below 2°C above pre-industrial levels while pursuing efforts to restrict warming to 1.5°C. Under this framework, countries submit NDCs outlining their commitments to reduce greenhouse gas emissions, strengthen climate resilience and promote sustainable development. India's updated NDC (2022) includes the commitment to create an additional carbon sink of 2.5–3.0 billion tonnes of CO<sub>2</sub> equivalent by 2030 through increased forest and tree cover. Agroforestry provides one of the most practical and scalable approaches to achieving this target by increasing tree cover outside forests, enhancing carbon sequestration, improving soil organic carbon, reducing dependence on synthetic fertilizers, increasing nutrient-use efficiency, conserving soil and water resources, and strengthening resilience against droughts, floods and other climate-induced stresses.

Beyond supporting India's NDCs, agroforestry contributes to several national and global sustainability initiatives, including the Green

India Mission, Climate-Smart Agriculture (CSA), Land Degradation Neutrality (LDN), the Sustainable Development Goals (SDGs) and the vision of Viksit Bharat @2047. It directly supports SDG 1 (No Poverty), SDG 2 (Zero Hunger), SDG 6 (Clean Water and Sanitation), SDG 12 (Responsible Consumption and Production), SDG 13 (Climate Action) and SDG 15 (Life on Land) by improving soil health, conserving biodiversity, restoring degraded landscapes, enhancing water conservation, diversifying farm income and strengthening rural livelihoods. By combining climate mitigation, climate adaptation and sustainable agricultural development, agroforestry offers a comprehensive pathway for achieving food security, environmental conservation and long-term resilience while creating additional income opportunities for farmers through emerging carbon markets.

## Conclusion

Agroforestry is far more than planting trees on farms. It is a holistic approach that integrates agricultural production with ecological sustainability. By improving soil health, conserving water, enhancing biodiversity, sequestering carbon and diversifying farm income, agroforestry strengthens both climate resilience and rural livelihoods. Assam's traditional Bari system exemplifies how indigenous knowledge can successfully combine productivity with environmental conservation. As India moves towards Viksit Bharat @2047, integrating traditional wisdom with scientific innovation, supportive policies and digital technologies can transform agroforestry into a powerful tool for restoring degraded landscapes, achieving the country's climate commitments, and ensuring sustainable agriculture and prosperous farming communities for future generations.

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# Plant-derived Antimicrobials as Future Biopesticides: Opportunities and Regulatory Challenges

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Growing concerns about pesticide resistance, environmental pollution and food safety have increased global interest in plant-derived antimicrobials (PDAs) as sustainable biopesticides. These natural compounds, including phenolics, terpenoids, alkaloids, flavonoids, saponins and essential oils, are effective against many plant pathogens such as fungi, bacteria, nematodes and viruses. Because they are biodegradable, environmentally friendly and compatible with Integrated Pest Management (IPM) programs, they are considered promising alternatives to synthetic pesticides. However, their large-scale use is still limited due to complex regulations, inconsistent performance under field conditions, poor formulation stability and the lack of standardized methods for residue and toxicity evaluation. The study includes the chemical diversity, modes of action, recent developments, commercial potential and regulatory challenges of plant-derived antimicrobial-based biopesticides. It also highlights the need for better regulations, improved formulations and more field-based studies on their effectiveness and safety to promote their wider adoption in sustainable agriculture.

## Introduction

The global pesticide market mainly depends on synthetic agrochemicals, which have helped increase crop production. However, their excessive and improper use has caused several problems, including pesticide resistance in pathogens, soil and water pollution, pesticide residues in food, harmful effects on beneficial microorganisms and risks to human health (Pretty & Bharucha, 2015). In addition, climate change and continuous cultivation of the same crop (monoculture) have increased disease outbreaks and helped plant pathogens evolve more rapidly.

Plants naturally produce bioactive compounds, known as plant-derived antimicrobials, to protect themselves from diseases and pests. These natural compounds provide an environmentally friendly option for plant disease management. More than 2,500 plant species are known to have pesticidal properties and over 120 plant-based biopesticides are commercially available worldwide (Isman, 2020).

Increasing demand for organic and residue-free food, along with global efforts such as the FAO's sustainable plant protection initiatives, has encouraged more research and wider use of these botanical products.

## Chemical Diversity and Mechanisms of Action

Plants produce structurally diverse antimicrobial metabolites exhibiting different modes of action, reducing risk of resistance development.

**Terpenoids and Essential Oils:** Obtained from species like neem (*Azadirachta indica*), eucalyptus, citronella, clove and oregano, essential oils contain monoterpenes and sesquiterpenes with strong antifungal and antibacterial properties. Their lipophilic nature enables penetration of microbial membranes, altering permeability, ATP synthesis, respiration and enzyme activity (Bakkali *et al.*, 2008).



**Phenolics and Polyphenols:** Compounds such as tannins, coumarins, phenolic acids and flavonoids inhibit spore germination, quorum sensing and oxidative metabolism. Chickpea, sorghum and soybean produce phytoalexins such as maackiain and genistein with strong antifungal effects (Parker *et al.*, 2022).

**Alkaloids:** Nicotine, berberine, reserpine and capsaicin disrupt neural signalling in insects and modify membrane dynamics, offering dual insecticidal and antibacterial action.

**Saponins:** Steroidal and triterpenoid saponins from quinoa, tea and horse chestnut exhibit membrane-disrupting antifungal activity and immune-priming effects in plants.

**Sulfur-Containing Compounds:** Allicin in garlic and glucosinolates in brassicas generate reactive sulfur species, inhibiting microbial protein synthesis.

The structural diversity, multi-target activity and natural origin make PDAs ideal candidates for next-generation biopesticides.

### Advantages and Research Opportunities

**Environmentally Sustainable:** PDAs are biodegradable, pose minimal ecological toxicity and preserve soil microbial diversity (Chandler *et al.*, 2011). They fit well within organic and low-input agricultural systems.

**Low Resistance Risk:** Multiple sites of action reduce pathogen adaptation potential compared to single-target synthetic fungicides.

**Compatibility with IPM:** Botanical antimicrobials integrate well with biological control agents, cultural practices, reduced-risk fungicides and host resistance strategies.

**Market Growth Potential:** The global biopesticide market is projected to grow from USD 6.5 billion in 2023 to USD 14 billion by 2030, with botanicals

being the fastest-growing segment (Markets & Markets, 2023).

### Novel Sources and Approaches:

- Endophytic plant metabolites
- Metabolomics-guided natural compound discovery
- CRISPR-based metabolic pathway enhancement
- AI-driven compound screening
- Nanocarrier-assisted delivery systems

### Limitations and Technological Challenges

**Variability in Chemical Composition:** Environmental conditions, genotype, soil and extraction methods influence metabolite content and field efficacy.

**Poor Stability and Volatility:** Essential oils degrade rapidly under sunlight, temperature or oxidation, requiring formulation improvements.

**Limited Field-scale Validation:** Most studies remain laboratory or greenhouse-based. Long-term, multi-location trials are sparse.

**High Production and Extraction Costs:** Commercial scalability remains a concern for many botanicals.

**Lack of Awareness and Market Accessibility:** Smallholder farmers face limited access to botanical products.

Advancements in microencapsulation, nano-emulsion formulations, slow-release matrices and co-application with bioagents can overcome these issues.



## Regulatory Framework and Policy Barriers

Regulation plays a decisive role in biopesticide commercialization, yet global guidelines lack uniformity.

**United States:** The U.S. Environmental Protection Agency (EPA) provides a relatively streamlined registration pathway for biopesticides, requiring reduced toxicological data due to low-risk profiles. However, product-specific efficacy data remain necessary (EPA, 2022).

**European Union:** The EU follows stricter regulations under Regulation (EC) No. 1107/2009, with lengthy approval processes, extensive ecotoxicology requirements and limited botanical product approvals (Marrone, 2019).

**India and Developing Countries:** India's Central Insecticides Board and Registration Committee (CIBRC) recognizes biopesticides, but lengthy bureaucratic procedures, inadequate quality control and lack of standardized analytical guidelines delay commercialization.

### Key Regulatory Challenges:

- Absence of global harmonization
- Overlapping classification between botanical extracts and natural pesticides
- Limited residue and toxicological threshold standards
- Intellectual property complexities traditional knowledge vs. patents
- Need for standardized quality and purity testing

Developing internationally harmonized botanical biopesticide regulations would accelerate innovation and global trade.

## Future Prospects and Strategic Recommendations

- To strengthen PDAs as mainstream phyto-protection tools:
- Standardize extraction, formulation and quality assessment protocols
- Establish international databases for botanical pesticidal compounds
- Promote multi-institutional field evaluation networks
- Support farmer training, commercialization incentives and public-private partnerships
- Combine botanicals with microbial biocontrol agents for synergistic activity
- Utilize nanotechnology for stability, slow release and targeted delivery
- Develop AI-based toxicity prediction and risk assessment tools
- Encourage faster but risk-sensitive regulatory approval pathways

## Conclusion

Plant-derived antimicrobials offer a promising path toward environmentally responsible, residue-free crop protection. Their biochemical diversity, multi-targeted antimicrobial mechanisms and compatibility with sustainable agriculture make them strong candidates to replace or complement synthetic pesticides. However, to translate laboratory evidence into large-scale agricultural impact, regulatory harmonization, formulation innovations and long-term field efficacy research are essential. With scientific, industrial and policy collaboration, botanical biopesticides can significantly contribute to global food safety, environmental resilience and climate-smart agriculture.





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# Sugarcane Production in Maharashtra: Status, Innovations and Sustainability

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Sugarcane is one of the most important commercial crops in Maharashtra and plays a pivotal role in the state's agricultural economy, agro-industrial development and rural livelihoods. Maharashtra is among the leading sugarcane-producing states in India, supported by an extensive network of cooperative and private sugar factories, advanced irrigation infrastructure and widespread adoption of improved production technologies. The increasing use of drip irrigation, fertigation, high-yielding varieties, mechanization and scientific crop management practices has significantly enhanced sugarcane productivity and resource-use efficiency. The sugarcane sector also contributes substantially to sugar production, ethanol manufacturing, cogeneration of electricity and value addition through by-products such as bagasse, molasses and press mud.

Despite these achievements, sugarcane cultivation in Maharashtra faces several challenges, including declining soil organic carbon, nutrient imbalance, salinity and waterlogging, shortage of quality seed cane, increasing incidence of pests and diseases, climate variability, water scarcity, rising input costs, labour shortages and limited adoption of climate-smart technologies in certain regions. Addressing these constraints requires integrated approaches involving sustainable soil and water management, improved seed systems, precision nutrient management, mechanization, digital agriculture and climate-resilient production technologies.

This chapter presents a comprehensive overview of the current status of sugarcane cultivation in Maharashtra, highlighting its geographical distribution, production characteristics, technological advancements, industrial significance and major production constraints. It also emphasizes the role of research institutions, agricultural universities, extension agencies and the sugar industry in promoting sustainable and climate-resilient sugarcane production. The chapter provides valuable information for researchers, students and extension personnel involved in the sugarcane sector and serves as a useful reference for developing strategies to enhance productivity, profitability and long-term sustainability of sugarcane cultivation in Maharashtra.

## Introduction

Sugarcane is one of the most important commercial crops in Maharashtra and occupies a prominent position in the state's agricultural economy. The crop forms the backbone of the cooperative and private sugar industries, ethanol production, cogeneration of electricity, jaggery manufacturing, and provides livelihood to millions of farmers and workers associated with the sugar sector. The expansion of irrigation facilities, adoption of improved sugarcane varieties, widespread use of drip irrigation, and

advances in crop management technologies have enabled Maharashtra to emerge as one of the leading sugarcane-producing states in India (Agricultural Statistics at a Glance, 2024; Directorate of Economics and Statistics, 2024; Vasantdada Sugar Institute, 2024).

Sugarcane is cultivated annually on approximately **1.3–1.4 million hectares** in Maharashtra. Western Maharashtra constitutes the principal sugarcane belt because of favorable climatic conditions, reliable irrigation facilities, and a well-developed network of



cooperative and private sugar factories. The major sugarcane-growing districts include Pune, Satara, Sangli, Kolhapur, Solapur, Ahmednagar and Nashik, while cultivation has expanded in districts such as Nanded, Latur, Dharashiv (Osmanabad) and Parbhani (Directorate of Sugar, 2024; Maharashtra State Agriculture Department, 2024).

### **Salient Features of Sugarcane Cultivation in Maharashtra**

Maharashtra has developed one of the most progressive and technologically advanced sugarcane production systems in India. The state's success is attributed to strong institutional support, scientific research, efficient irrigation practices, adoption of improved varieties, and a well-established sugar industry. These factors have enabled Maharashtra to achieve high productivity while promoting resource-use efficiency and sustainability.

### **Leading Sugarcane-Producing State**

Maharashtra is among the leading sugarcane-producing states in India, contributing significantly to the country's sugar production. Although the state accounts for a relatively smaller share of the national sugarcane area compared with Uttar Pradesh, it consistently records higher cane productivity and sugar recovery due to scientific cultivation practices, better irrigation management, and the cultivation of superior sugarcane varieties. The state's sugar industry plays a crucial role in the national economy through sugar, ethanol, and renewable energy production (Solomon, 2016).

### **Technology-Driven Sugarcane Cultivation**

Sugarcane cultivation in Maharashtra is highly technology-oriented. Farmers have increasingly adopted scientific crop production technologies, including precision land preparation, quality planting material, mechanized planting, improved nutrient management, integrated pest management, and digital advisory services. The integration of research

findings into farmers' fields has considerably improved productivity and profitability.

### **Leadership in Drip Irrigation Adoption**

Maharashtra has emerged as the national leader in the adoption of drip irrigation for sugarcane cultivation. Large-scale implementation of micro-irrigation has significantly reduced water consumption while increasing cane yield and sugar recovery. Drip irrigation ensures uniform moisture availability, minimizes evaporation and runoff losses, suppresses weed growth, and improves irrigation efficiency. It is particularly important under the prevailing conditions of limited water availability and increasing climatic variability (IISR, 2023).

### **Efficient Water Management through Micro-Irrigation**

Micro-irrigation technologies, including drip systems, are extensively utilized to maximize water-use efficiency. These systems allow precise application of irrigation water directly to the root zone, reducing conveyance losses and improving water productivity. The adoption of drip irrigation has also facilitated fertigation, enabling simultaneous application of water and nutrients with greater precision.

### **Adoption of Improved Sugarcane Varieties**

Farmers in Maharashtra cultivate improved, high-yielding, early- and mid-late-maturing sugarcane varieties possessing superior sugar recovery and tolerance to major diseases. Continuous varietal improvement programmes undertaken by research institutions and agricultural universities have resulted in the release of improved cultivars suited to different agro-climatic regions of the state. Adoption of disease-resistant varieties has contributed significantly to stable productivity.



## **Strong Extension and Farmer Support Systems**

Farmers receive continuous technical guidance through organized sugarcane development programmes conducted by agricultural universities, research institutions, and sugar factories. Extension programmes include field demonstrations, farmer training, exposure visits, advisory services, and capacity-building programmes that promote adoption of improved production technologies.

## **Role of Cane Development Departments**

Most cooperative and private sugar factories maintain dedicated Cane Development Departments that provide technical assistance throughout the crop cycle. These departments supply quality seed cane, recommend improved production technologies, monitor crop growth, assist in pest and disease management, and coordinate harvesting and transportation. Their close interaction with farmers has significantly strengthened technology transfer.

## **Soil Test-Based Nutrient Management**

Scientific nutrient management based on soil testing has gained considerable acceptance among sugarcane growers. Soil analysis enables site-specific fertilizer recommendations that improve nutrient-use efficiency, reduce unnecessary fertilizer application, lower production costs, and minimize environmental degradation. Balanced fertilization also contributes to sustained soil fertility and higher cane yields.

## **Increasing Use of Biofertilizers and Organic Inputs**

The application of biofertilizers, farmyard manure, compost, press mud, green manures, and micronutrients has increased substantially in recent years. These inputs improve soil physical, chemical, and biological properties while enhancing nutrient availability and soil organic carbon. Integrated nutrient management practices are increasingly recommended for sustainable sugarcane production.

## **Growing Mechanization**

Mechanization has expanded rapidly in sugarcane cultivation. Modern machinery is being adopted for land preparation, trench opening, planting, fertilizer application, earthing-up, trash shredding, intercultural operations, and harvesting. Mechanization addresses labour shortages, improves operational efficiency, reduces production costs, and ensures timely field operations.

## **Fertigation through Drip Irrigation**

Fertigation has become an integral component of modern sugarcane cultivation in Maharashtra. Application of water-soluble fertilizers through drip irrigation allows nutrients to be supplied directly to the active root zone according to crop growth stages. This practice improves fertilizer-use efficiency, reduces nutrient losses, lowers fertilizer requirements, and enhances cane yield and sugar recovery.

## **Adoption of Sustainable Crop Management Practices**

Sustainable agronomic practices such as sugarcane trash mulching, intercropping with legumes, conservation tillage, and residue recycling are increasingly adopted by progressive farmers. Trash mulching conserves soil moisture, suppresses weeds, moderates soil temperature, reduces evaporation losses, and gradually improves soil organic matter through decomposition.

## **Bud-Chip Nursery Technology**

Bud-chip technology has emerged as an efficient method for producing healthy sugarcane seedlings using a smaller quantity of seed cane. This technique reduces seed requirement by nearly 80–90%, facilitates rapid multiplication of improved varieties, and ensures the availability of disease-free planting material. It has become an important component of sustainable seed cane production systems.



### **Adoption of Modern Production Technologies**

Modern production technologies such as precision planting, laser land levelling, mechanized cultivation, remote sensing, Geographic Information Systems (GIS), drones, Internet of Things (IoT)-based irrigation systems, and artificial intelligence-based decision support are gradually being introduced to improve crop monitoring, input management, and overall farm productivity.

### **Integration with the Sugar and Bioenergy Industries**

Sugarcane cultivation in Maharashtra is closely integrated with the sugar manufacturing, ethanol, and renewable energy sectors. This strong agro-industrial linkage ensures a stable market for farmers while promoting value addition and diversification within the sugar industry. Government policies promoting ethanol blending have further strengthened this relationship.

### **Efficient Utilization of Sugarcane By-products**

The Maharashtra sugar industry efficiently utilizes sugarcane by-products, thereby enhancing economic returns and minimizing waste generation. Bagasse, molasses, and press mud are converted into valuable industrial products, contributing to the circular bioeconomy.

### **Cogeneration of Electricity from Bagasse**

Bagasse, the fibrous residue remaining after juice extraction, serves as an important renewable fuel for cogeneration of electricity in sugar factories. Many factories generate surplus electricity beyond their internal requirements and export it to the state power grid, contributing to renewable energy generation and reducing dependence on fossil fuels.

### **Molasses for Ethanol Production**

Molasses is the principal raw material for ethanol production in Maharashtra. Expansion of ethanol

distilleries under the Government of India's Ethanol Blended Petrol Programme has significantly increased the demand for molasses and sugarcane juice, thereby providing additional income opportunities for sugar factories and farmers.

### **Press Mud as Organic Manure**

Press mud, a by-product of sugar processing, is increasingly utilized as an organic manure due to its high organic matter and nutrient content. Application of press mud improves soil fertility, enhances microbial activity, increases water-holding capacity, and contributes to long-term soil health.

### **Promotion of Climate-Resilient Technologies**

Considering increasing water scarcity and climate variability, climate-resilient production technologies are receiving greater emphasis. These include drought-tolerant varieties, precision irrigation, deficit irrigation scheduling, trash mulching, integrated nutrient management, digital weather advisories, and climate-smart crop management practices aimed at improving resilience and resource-use efficiency.

### **Contribution of Research and Extension Institutions**

The continuous advancement of sugarcane cultivation in Maharashtra has been largely driven by collaborative efforts of Vasantdada Sugar Institute (VSI), ICAR–Indian Institute of Sugarcane Research (IISR), State Agricultural Universities, the Department of Agriculture, and cooperative and private sugar factories. These organizations conduct research, develop improved production technologies, produce quality planting material, organize farmer training programmes, and facilitate effective transfer of technology to farming communities.

### **Employment Generation**

Sugarcane cultivation is one of the largest sources of rural employment in Maharashtra. It creates employment opportunities throughout the value





chain, including nursery production, field operations, harvesting, transportation, sugar manufacturing, ethanol production, power generation, and allied industries. The sector supports the livelihoods of millions of farmers, agricultural labourers, transport workers, and factory employees.

### Strong Institutional Support

The extensive network of cooperative and private sugar factories provides a unique institutional framework for sugarcane development in Maharashtra. These factories facilitate access to quality seed cane, extension services, mechanization, credit support, input supply, harvesting arrangements, and assured marketing of sugarcane, thereby strengthening the production system.

### Foundation of Maharashtra's Agricultural Economy

Sugarcane remains one of the most important pillars of Maharashtra's agricultural economy. Besides contributing substantially to agricultural income and industrial development, the crop supports rural infrastructure, employment generation, renewable energy production, and biofuel security. Continued technological innovation, sustainable resource management, and institutional collaboration will further strengthen the long-term sustainability and competitiveness of sugarcane cultivation in the state (Solomon, 2016; IISR, 2023; VSI, 2024).

### Major Challenges in Sugarcane Cultivation in Maharashtra

Despite remarkable technological progress, sugarcane cultivation in Maharashtra continues to face several agronomic, environmental and socio-economic challenges (IISR, 2023; VSI, 2024).

#### Soil Health

- Declining soil organic carbon.
- Imbalanced nutrient management.

- Soil salinity, sodicity, alkalinity and waterlogging.
- Continuous monocropping leading to soil degradation.

#### Seed and Planting Material

- Lack of regular seed replacement.
- Shortage of certified disease-free seed cane.
- Continued dependence on conventional three-budded setts.
- Poor germination (approximately 60–70%).

#### Crop Management

- Delayed planting and improper intercultural operations.
- Poor weed management.
- Inadequate adoption of recommended production technologies.

#### Pest and Disease Incidence

- Increasing occurrence of red rot, smut, grassy shoot disease and wilt.
- Higher incidence of whitefly, early shoot borer, internode borer, pyrilla and woolly aphid.

#### Climate Change

- Erratic rainfall.
- Frequent droughts and prolonged dry spells.
- Heavy rainfall and flooding.
- Increasing irrigation water scarcity.

#### Labour and Mechanization

- Acute shortage of skilled labour.
- Rising labour costs.



- Limited adoption of mechanized harvesting.

### Increasing Cost of Cultivation

- Rising prices of fertilizers, pesticides, fuel and quality planting material.
- Increased production costs reducing farm profitability.

### Technology Adoption

- Limited adoption of precision agriculture and digital technologies.
- Inadequate use of artificial intelligence, remote sensing and decision-support systems.
- Slow adoption of climate-smart and sustainable sugarcane production technologies (Singh et al., 2018; Solomon, 2016).

### Conclusion

Sugarcane cultivation occupies a strategic position in Maharashtra's agricultural and industrial economy. The state has achieved substantial progress through improved varieties, drip irrigation, mechanization and institutional support from research organizations and sugar industries. However, declining soil health, water scarcity, climate variability, pest and disease outbreaks, labour shortages and increasing production costs continue to threaten sustainable sugarcane production. Future development of the sector will depend on wider adoption of climate-smart agriculture, precision farming, quality seed systems, efficient water and nutrient management, mechanization and digital technologies for enhancing productivity and resource-use efficiency (ICAR, 2023; IISR, 2023; VSI, 2024).

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# Algae: The Green Gold Driving a Sustainable Future

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Algae are among the oldest and most diverse photosynthetic organisms on Earth and have emerged as one of the most promising renewable biological resources for sustainable development. Their exceptional capacity to convert sunlight, carbon dioxide and water into valuable biomass makes them indispensable for addressing global challenges related to food security, renewable energy, environmental protection and climate change. Besides contributing nearly half of the Earth's oxygen production, algae serve as an important source of proteins, essential fatty acids, vitamins, minerals, pigments and bioactive compounds. This article reviews the biology and classification of algae and highlights their multifaceted applications in agriculture, environmental management, food and nutraceutical industries, pharmaceuticals, wastewater treatment and biofuel production. The use of algae as biofertilizers, biostimulants and soil conditioners has gained considerable attention due to their ability to improve soil fertility, nutrient availability, crop productivity and stress tolerance. Furthermore, algal biomass is increasingly being explored for the production of biodiesel, bioethanol, biogas, biohydrogen and biodegradable bioplastics, contributing to the transition toward a circular bioeconomy. Recent advances in artificial intelligence-assisted cultivation, genetic engineering and integrated algal biorefineries are enhancing the commercial feasibility of algae-based technologies. Despite challenges associated with cultivation, harvesting and processing, continued technological innovations are expected to unlock the enormous potential of algae as a sustainable green resource for future generations.

## Introduction

Algae are simple photosynthetic organisms that inhabit a wide range of aquatic and terrestrial environments, including freshwater, marine ecosystems, moist soils and even extreme habitats such as deserts and snow-covered regions. They range in size from microscopic unicellular microalgae to giant multicellular seaweeds extending several metres in length. Unlike higher plants, algae lack true roots, stems, leaves and vascular tissues, yet they perform photosynthesis with remarkable efficiency and contribute significantly to global primary productivity.

Often referred to as the "**Green Gold**" of the twenty-first century, algae have attracted worldwide attention because of their rapid growth, high biomass productivity and ability to utilize sunlight and atmospheric carbon dioxide efficiently. Scientists

estimate that algae contribute nearly **50% of the Earth's oxygen production**, making them indispensable for sustaining life on the planet. In addition to their ecological importance, algae provide sustainable solutions for renewable energy, environmental remediation, food and nutrition, agriculture, pharmaceuticals, cosmetics and industrial biotechnology.

The increasing demand for environmentally friendly technologies has accelerated research into algal biotechnology. Microalgae such as *Chlorella* and *Spirulina* are recognized globally as nutrient-rich functional foods, while macroalgae provide commercially important compounds such as agar, alginate and carrageenan. Algae are also emerging as promising feedstocks for biofuel production because they grow rapidly without competing for fertile agricultural land or freshwater resources.



The integration of algae into agriculture has further strengthened their importance. Algae-based biofertilizers and biostimulants improve soil fertility, stimulate plant growth, enhance nutrient uptake and increase crop tolerance to environmental stresses. Similarly, algae-based wastewater treatment and carbon capture technologies contribute to environmental sustainability by removing pollutants and reducing greenhouse gas emissions.

Considering their wide-ranging applications and their potential to support several United Nations Sustainable Development Goals (SDGs), algae are increasingly recognized as a key biological resource for building a cleaner, greener and more sustainable future.



## 2. What are Algae?

Algae are a diverse group of chlorophyll-containing photosynthetic organisms that occur in freshwater, marine and terrestrial ecosystems. They are among the earliest life forms on Earth and play a fundamental role in maintaining ecological balance by converting solar energy into organic matter through photosynthesis. Unlike higher plants, algae lack true roots, stems, leaves and vascular tissues;

however, they possess specialized pigments that enable them to efficiently capture sunlight and synthesize food.

Algae exhibit remarkable diversity in size and morphology. They range from microscopic unicellular species, known as microalgae, to large multicellular seaweeds, commonly referred to as macroalgae, which may reach several metres in length. Owing to their rapid growth, high photosynthetic efficiency and ability to thrive under diverse environmental conditions, algae have become valuable biological resources for food, agriculture, pharmaceuticals, environmental management and renewable energy production.

The scientific study of algae is known as **Phycology (Algology)** and the increasing global demand for sustainable resources has significantly expanded research in this field.

**Table 1. Major Groups of Algae and Their Economic Importance**

| Algal Group                        | Major Pigments                    | Representative Genera               | Major Applications               |
|------------------------------------|-----------------------------------|-------------------------------------|----------------------------------|
| Green algae ( <i>Chlorophyta</i> ) | Chlorophyll <i>a</i> and <i>b</i> | <i>Chlorella</i> , <i>Ulva</i>      | Food, feed, biofuel              |
| Brown algae ( <i>Phaeophyta</i> )  | Fucoxanthin                       | <i>Laminaria</i> , <i>Sargassum</i> | Alginate production, fertilizers |
| Red algae ( <i>Rhodophyta</i> )    | Phycocyanin                       | <i>Gelidium</i> , <i>Gracilaria</i> | Agar and carrageenan production  |



|                                    |             |                                    |                                  |
|------------------------------------|-------------|------------------------------------|----------------------------------|
| Cyanobacteria (Blue-green algae)   | Phycocyanin | <i>Spirulina</i> , <i>Anabaena</i> | Biofertilizers, food supplements |
| Diatoms ( <i>Bacillariophyta</i> ) | Fucoxanthin | <i>Navicula</i>                    | Biofuel research, filtration     |

### 3. Why are Algae Called "Green Gold"?

Algae are increasingly referred to as **"Green Gold"** because of their exceptional productivity, environmental benefits and wide industrial applications. Unlike conventional crops, algae can be cultivated on non-arable land using saline or wastewater, thereby conserving fertile agricultural land and freshwater resources. Their rapid biomass production and efficient carbon dioxide fixation make them an attractive renewable resource for the emerging bioeconomy.

The growing interest in algae is driven by their ability to produce valuable products, including renewable biofuels, high-protein food supplements, pharmaceuticals, cosmetics, biodegradable plastics and agricultural biostimulants. In addition, algae contribute significantly to wastewater treatment, carbon sequestration and ecosystem restoration, making them an important tool for climate change mitigation and sustainable development.

#### Major Advantages of Algae

- High photosynthetic efficiency and rapid biomass production.
- Significant carbon dioxide sequestration potential.
- Cultivation without competing with food crops for fertile land.
- Rich source of proteins, vitamins, minerals, essential fatty acids and natural pigments.

- Valuable feedstock for renewable biofuels and green chemicals.
- Effective biofertilizers and plant biostimulants in sustainable agriculture.
- Efficient removal of nutrients and pollutants from wastewater.
- Renewable raw material for biodegradable bioplastics and circular bioeconomy initiatives.

These unique characteristics have positioned algae as one of the most promising biological resources for achieving food security, clean energy production, environmental sustainability and climate resilience in the twenty-first century.

### 4. Nutritional Importance of Algae

Algae are recognized as one of the most nutrient-dense biological resources and are increasingly incorporated into human and animal diets. Microalgae, particularly *Spirulina* and *Chlorella*, contain high-quality proteins, essential amino acids, polyunsaturated fatty acids, vitamins, minerals, antioxidants and natural pigments. Their rich nutritional profile has led to their widespread use in functional foods, nutraceuticals, dietary supplements and animal feed.

Apart from their nutritional value, algae produce bioactive compounds such as carotenoids, chlorophyll, phycocyanin and phenolic substances that exhibit antioxidant, anti-inflammatory, antimicrobial and immunomodulatory properties. These compounds contribute to improved human health and have attracted considerable interest from the pharmaceutical and food industries.

**Table 2. Approximate Nutritional Composition of Microalgae**

| Component | Approximate Content |
|-----------|---------------------|
| Protein   | 40–70%              |





|                    |                                       |
|--------------------|---------------------------------------|
| Lipids             | 10–50%                                |
| Carbohydrates      | 10–30%                                |
| Vitamins           | A, B-complex, C, D, E and K           |
| Minerals           | Iron, Calcium, Magnesium, Zinc        |
| Bioactive Pigments | Chlorophyll, Carotenoids, Phycocyanin |

### 5. Agricultural Applications of Algae

Algae have become valuable components of sustainable agriculture because they improve soil fertility, crop productivity and environmental quality. Blue-green algae (*Anabaena*, *Nostoc*) naturally fix atmospheric nitrogen and are widely used as biofertilizers, particularly in paddy cultivation. Their application enhances nutrient availability, improves soil microbial activity and reduces dependence on chemical fertilizers.

Seaweed extracts are extensively used as plant biostimulants because they contain natural plant growth regulators such as auxins, cytokinins, gibberellins, betaines, amino acids and micronutrients. These compounds stimulate seed germination, root development, flowering, fruit set and crop yield while improving tolerance to drought, salinity and temperature stress.

Algal biomass also serves as an excellent soil conditioner by increasing soil organic matter, improving soil aggregation, enhancing water-holding capacity and promoting beneficial microbial populations. Consequently, algae-based products contribute significantly to sustainable nutrient management and climate-resilient agriculture.

**Table 3. Agricultural Applications of Algae**

| Application            | Agricultural Benefit                                            |
|------------------------|-----------------------------------------------------------------|
| Biofertilizer          | Biological nitrogen fixation and improved nutrient availability |
| Biostimulant           | Enhanced plant growth, flowering and yield                      |
| Soil conditioner       | Improved soil structure and water retention                     |
| Compost additive       | Increased microbial activity and faster decomposition           |
| Animal feed supplement | Improved livestock nutrition and productivity                   |

### Benefits of Algae in Sustainable Agriculture

- Improves soil fertility and microbial diversity.
- Enhances nutrient-use efficiency.
- Promotes root growth and crop establishment.
- Increases tolerance to abiotic stresses.
- Reduces dependence on synthetic fertilizers.
- Supports environmentally sustainable farming systems.

The integration of algae into modern agriculture not only increases crop productivity but also contributes to soil health restoration, environmental conservation and the long-term sustainability of food production systems.

### 6. Role of Algae in Climate Change Mitigation

Climate change, driven primarily by increasing greenhouse gas emissions, is one of the greatest environmental challenges of the twenty-first century. Algae have emerged as an effective biological tool for mitigating climate change due to their exceptional capacity to absorb atmospheric carbon dioxide (CO<sub>2</sub>)



through photosynthesis. Compared with terrestrial plants, many microalgal species exhibit faster growth rates and higher carbon fixation efficiencies, enabling them to convert CO<sub>2</sub> into valuable biomass within a short period.

Large-scale cultivation of microalgae near industrial facilities and power plants has been proposed as a sustainable carbon capture strategy. The harvested biomass can subsequently be utilized for producing biofuels, fertilizers, animal feed and other value-added products, thereby contributing to a low-carbon circular economy.

### 7. Algae in Wastewater Treatment

Algal biotechnology has become an environmentally friendly approach for wastewater treatment and resource recovery. During growth, algae efficiently absorb excess nutrients such as nitrogen and phosphorus while simultaneously removing heavy metals, organic pollutants and dissolved carbon dioxide from wastewater.

The integration of algae into wastewater treatment systems not only improves water quality but also generates valuable biomass that can be utilized for biofuel production, composting and biofertilizer development. Consequently, algae-based wastewater treatment offers a sustainable solution for water purification while reducing the environmental impact of conventional treatment technologies.

### Major Pollutants Removed by Algae

- Nitrogen compounds
- Phosphorus compounds
- Heavy metals
- Organic pollutants
- Carbon dioxide

### 8. Biofuel Production from Algae

The increasing demand for renewable energy has positioned algae as one of the most promising feedstocks for next-generation biofuels. Unlike conventional energy crops, algae possess high lipid productivity, rapid biomass accumulation and the ability to grow on non-arable land using saline or wastewater. These characteristics minimize competition with food production while maximizing energy efficiency.

Depending on their biochemical composition, algal biomass can be converted into several renewable fuels, including biodiesel, bioethanol, biogas, biohydrogen and sustainable aviation fuel. These biofuels emit significantly lower greenhouse gases than fossil fuels and support global efforts toward clean and sustainable energy production.

**Table 4. Major Biofuels Produced from Algae**

| Biofuel                   | Primary Raw Material      | Major Application               |
|---------------------------|---------------------------|---------------------------------|
| Biodiesel                 | Lipid-rich microalgae     | Transportation fuel             |
| Bioethanol                | Carbohydrate-rich biomass | Fuel blending                   |
| Biogas                    | Whole algal biomass       | Electricity and heat generation |
| Biohydrogen               | Photosynthetic metabolism | Clean hydrogen energy           |
| Sustainable Aviation Fuel | Lipid fractions           | Aviation sector                 |

The commercialization of algae-based biofuels is expected to expand as technological advances reduce production costs and improve biomass harvesting and conversion efficiencies. With continued investment in research and industrial-scale cultivation systems, algae are likely to play a



significant role in achieving global energy security and reducing dependence on fossil fuels.

### 9. Pharmaceutical and Biomedical Applications

Algae are an important source of bioactive compounds with considerable pharmaceutical potential. Microalgae synthesize antioxidants, carotenoids, polyphenols, sulfated polysaccharides, omega-3 fatty acids, vitamins and pigments that exhibit antioxidant, antimicrobial, antiviral, anti-inflammatory, anticancer and immunomodulatory activities. These natural compounds are increasingly utilized in the development of nutraceuticals, pharmaceuticals, cosmetics and biomedical products. Ongoing research in algal biotechnology is expected to facilitate the discovery of novel therapeutic molecules for treating chronic diseases and improving human health.

### 10. Algae in Food and Nutraceutical Industries

The growing demand for sustainable and nutritious food has accelerated the commercialization of algae-based products. Species such as *Spirulina* and *Chlorella* are widely marketed as dietary supplements because of their high protein content and balanced nutritional composition. Algal biomass is incorporated into protein powders, tablets, functional beverages, bakery products, natural food colorants and omega-3 supplements.

In addition to improving nutritional quality, algae provide natural pigments and antioxidants that enhance food quality and shelf life. Their cultivation requires fewer natural resources than conventional crops, making algae an environmentally sustainable alternative protein source for the future.



### 11. Emerging Technologies in Algal Biotechnology

Rapid advances in biotechnology are transforming algae into an important platform for sustainable industrial development. Modern research focuses on improving biomass productivity, genetic enhancement and integrated biorefinery systems to maximize resource utilization. Emerging technologies include:

- Artificial intelligence-assisted cultivation and monitoring.
- Genetic engineering of microalgae for enhanced productivity.
- Carbon-negative algal biorefineries.
- Biodegradable bioplastics derived from algal biomass.
- Green hydrogen production.
- Living algal bio-batteries for low-energy electronic devices.
- Integrated circular bioeconomy systems for waste valorization.

These innovations are expected to improve commercial feasibility while expanding the role of algae in achieving global sustainability goals.

### 12. Conclusion

Algae represent one of the most versatile and sustainable biological resources available for addressing global challenges related to food security,



renewable energy, environmental conservation and climate change. Their exceptional photosynthetic efficiency, rapid biomass production and ability to grow on non-arable land make them an ideal renewable resource for the future.

The diverse applications of algae in agriculture, wastewater treatment, pharmaceuticals, food industries, carbon capture and biofuel production demonstrate their immense economic and ecological importance. Continued advancements in biotechnology, artificial intelligence and integrated biorefinery systems are expected to enhance the commercial viability of algae-based technologies. With sustained scientific innovation and policy support, algae have the potential to become a cornerstone of the global green economy and contribute significantly to achieving the United Nations Sustainable Development Goals (SDGs).

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# Agricultural Credit Access for Small and Marginal Farmers in Hill Agriculture

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Institutional credit remains central to reducing farmer dependence on high-cost informal lending, yet its reach continues to vary sharply across India's diverse agroecological zones. This article examines the state of agricultural credit access for small and marginal farmers in hill agriculture, using Himachal Pradesh as a reference case. Despite an expanding network of cooperative banks, regional rural banks and rising Kisan Credit Card (KCC) penetration, structural barriers, including fragmented landholdings, difficult terrain, thin banking infrastructure, and lending norms calibrated to plains-style cereal cropping, continue to push a meaningful share of small and marginal farmers toward informal credit at exploitative rates. Tribal and remote farming communities face compounded disadvantages in awareness and accessibility. The article outlines interventions, including horticulture-specific scales of finance, doorstep and mobile banking, and targeted financial literacy programmes, needed to close this gap.

## Introduction

Timely and adequate credit is widely recognised as a precondition for farmers to move beyond subsistence cultivation toward more commercial, productivity-enhancing farming. India's principal instrument for delivering this credit, the Kisan Credit Card scheme, was introduced in August 1998 following the recommendations of the R.V. Gupta committee, with the explicit aim of providing farmers hassle-free, collateral-light access to institutional finance in place of exploitative moneylending.

At the national level, uptake of institutional credit has genuinely improved over time. NABARD's second All India Rural Financial Inclusion Survey (NAFIS 2021-22), based on a sample of about one lakh rural households across all states and union territories, found that the share of agricultural households borrowing from institutional sources rose from 60.5 per cent in 2016-17 to 75.5 per cent in 2021-22 (NABARD, 2024). Under the Modified Interest Subvention Scheme administered jointly by the Reserve Bank of India and NABARD,

farmers can access short-term crop loans of up to ₹3 lakh at a nominal rate of 7 per cent per annum, which falls to an effective 4 per cent for those who repay on time (RBI 2024). Yet the same NAFIS round also found that roughly a quarter of rural households could not operate an ATM independently and about three-fifths needed assistance to use mobile banking, a digital-access gap with particular relevance for remote hill terrain. Earlier NABARD survey rounds had also flagged Himachal Pradesh among the states with comparatively high household indebtedness, underlining that formal credit expansion and household debt stress can rise together when access to affordable institutional credit remains incomplete.

## The Credit Landscape in Himachal Pradesh

Farmers in Himachal Pradesh draw on three main institutional channels: commercial banks, regional rural banks such as the Himachal Pradesh Gramin Bank, and cooperative banks such as the Himachal Pradesh State Co-operative Bank, all of which offer KCC-linked crop and term loans for cultivation, post-harvest expenses, and allied activities like dairying





(HP Gramin Bank, n.d.; HP State Co-operative Bank, n.d.). Studies tracking KCC performance in the state over 2017-2023 report a positive and growing trend in both the number of operative cards and the amount sanctioned, with cooperative banks playing the pivotal role in this expansion.

Even so, ground-level surveys tell a more cautious story at the household level. One district-level study estimated that about 5 per cent of total credit needs among marginal and small farmers in the state were still being met through non-institutional sources, at interest rates as high as 24 per cent per annum, a clear indicator of persistent last-mile gaps despite the formal scheme's presence. This figure applies specifically to the marginal and small-farmer segment. Across its full sample of farm households, the same study also found average debt of roughly ₹1.23 lakh per household and ₹41,878 per hectare, with the debt burden per hectare highest among marginal farmers, meaning the smallest holders carry proportionally the heaviest debt loads relative to their landholding.

### **Structural Barriers Specific to Hill Agriculture**

Landholding fragmentation and collateral norms present the first barrier. KCC credit limits are typically computed as a scale of finance per crop multiplied by the area cultivated. This formula, designed around plains-style cereal cultivation, tends to understate the actual capital needs of high-value horticultural crops common in the hills, such as apple and stone fruit, which require substantially more investment per unit area than grain crops, even as hill landholdings themselves are smaller and more fragmented than the plains average.

Banking access and terrain compound this problem. Lower branch density and longer travel times in hilly terrain raise the effective non-interest cost of borrowing, including application visits, waiting time and travel expenses, even where the nominal interest rate is subsidised to near-zero for

prompt repayers. For farmers in remote blocks, these costs can outweigh the benefit of a lower headline interest rate, a pattern consistent with the NAFIS finding on limited independent use of digital banking channels in rural areas generally.

Crop-cycle mismatch is a further structural issue. Standard short-term crop loan cycles, typically renewed annually, do not always align well with the multi-year investment and long gestation periods of perennial horticultural crops. This creates friction between a lending model built around annual cereal cropping and the realities of orchard-based hill agriculture.

Finally, tribal and remote communities face compounded disadvantage. Research comparing tribal and non-tribal farming households in the state finds that tribal farmers face distinctly greater difficulty in awareness of loan schemes, physical accessibility to financial institutions, and securing adequate loan amounts, even though interest rates themselves are not typically flagged as the primary concern. Non-interest costs, such as documentation, service charges, and travel, emerge instead as the binding constraint for these households.

### **Policy Directions**

Addressing these gaps requires calibrating credit delivery to hill-specific realities rather than extending plains-designed instruments unchanged. A revised, horticulture-specific scale of finance that better reflects the real per-hectare investment needs of high-value hill crops would align sanctioned credit limits more closely with actual farmer requirements. Doorstep and mobile banking vans, along with periodic camp-based KCC issuance drives targeting remote and tribal blocks, would help offset the non-interest travel and access costs that current data suggest are a bigger deterrent than interest rates themselves. Greater integration of credit delivery with Farmer Producer Organisations, Self-Help Groups and Joint Liability Groups, already used as



collateral-light lending channels for smallholders, could further reduce documentation burdens for individual farmers. Dedicated financial literacy and outreach campaigns, designed specifically around the awareness gaps identified among tribal farming households, would complement infrastructure-side reforms. Finally, simplifying KYC verification and renewal processes, with assisted digital banking support rather than an assumption of independent digital access, could meaningfully cut the travel-related costs that currently erode the benefit of subsidised interest rates in remote hill terrain.

### Conclusion

Institutional credit expansion in hill states cannot be measured by card counts alone. The evidence from Himachal Pradesh suggests that even where KCC issuance is rising in line with national trends, a meaningful share of small and marginal farmers, particularly in remote and tribal areas, continue to rely on costly informal credit because formula-driven lending norms and thin banking infrastructure do not fit hill terrain or horticultural cropping patterns. Closing this gap will require credit delivery systems tailored to the capital intensity of hill crops and the access constraints of hill geography, rather than a uniform national template.

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# Agrovoltaics: A Sustainable Integration of Agriculture and Solar Energy

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Agriculture is the backbone of food security, while energy is essential for modern development. With increasing population, climate change, and limited land resources, it is becoming challenging to meet both food and energy demands simultaneously. In this context, agrovoltaics (also called agrivoltaics or agri-PV) has emerged as an innovative and sustainable solution. It refers to the simultaneous use of agricultural land for crop production and solar energy generation by installing photovoltaic (PV) panels above or between crops. This concept allows farmers to produce food and renewable energy from the same land area, improving land productivity and promoting sustainable agriculture. These systems can provide shade, reduce water loss, and create a favorable microclimate for crop growth while generating clean electricity.

## Concept of Agrovoltaics

Concept of Agrovoltaics Agrovoltaics is a dual land-use system in which solar panels are installed at a height above farmland so that crops can grow underneath or between the panel structures. In this system, sunlight is shared between solar panels and plants. The solar panels capture part of the solar radiation to generate electricity, while the remaining light reaches the crops for photosynthesis. Proper design and spacing of panels ensure that crops receive sufficient sunlight for growth. The panels are usually installed on elevated structures (around 2–5 meters high), allowing farm machinery and agricultural activities such as sowing, irrigation, and harvesting to be carried out normally.

## Working Principle of Agrovoltaic Systems

The agrovoltaic system works on the principle of sharing sunlight between energy production and crop growth.

1. **Solar panels absorb part of the sunlight** and convert it into electricity.
2. **The remaining sunlight reaches the crops**, enabling photosynthesis.

3. **Partial shading from panels reduces soil temperature and evaporation**, improving soil moisture retention.
4. The electricity generated can be used for farm operations such as irrigation pumps, lighting, cold storage, and other agricultural machinery.

In some systems, livestock such as sheep are allowed to graze between solar panels, helping control weeds and maintain vegetation naturally.

## Types of Agrovoltaic Systems

### 1. Elevated Solar Panel Systems

Solar panels are mounted on tall structures above crop fields. This is the most common agrovoltaic design and allows normal farming activities below the panels.



Fig 1. Elevated solar panel



## 2. Inter-Row Solar Panels

Solar panels are installed in rows with sufficient spacing between them so crops can grow between the panel structures.

## 3. Vertical Solar Panels

Panels are installed vertically along crop rows. This system reduces shading while producing electricity during morning and evening hours.



Fig 2. Vertical solar panel

## 4. Greenhouse Agrovoltaics

Semi-transparent solar panels are integrated with greenhouse roofs to produce energy while allowing light for plant growth.



Fig 3. Greenhouse agrovoltaics

## Crops Suitable for Agrovoltaic Systems

Not all crops respond equally to shading. Crops that tolerate partial shade perform well under agrovoltaic systems. Examples include:

- Leafy vegetables (lettuce, spinach)
- Tomatoes and peppers
- Potatoes
- Beans and pulses
- Fodder crops
- Some horticultural crops

Studies have shown that crops such as tomatoes, lettuce, and forage crops often show improved growth under solar panels due to reduced heat stress and improved soil moisture conditions.

## Advantages of Agrovoltaics

### 1. Improved Land Use Efficiency

Agrovoltaics allows the same land to be used for both agriculture and energy production. This can increase land productivity significantly compared with separate systems.

### 2. Increased Crop Yield

The partial shade provided by solar panels protects crops from extreme heat and excessive sunlight. Studies have shown crop yield improvements ranging from 20–60% in some crops.

### 3. Water Conservation

Solar panels reduce evaporation from soil by providing shade. This helps retain soil moisture and can reduce irrigation requirements by about 20–30%.

### 4. Renewable Energy Generation

Agrovoltaic systems produce clean solar energy that can be used on farms or sold to the electricity grid, helping reduce dependence on fossil fuels.





## 5. Additional Income for Farmers

Farmers can earn from both crop production and electricity generation, increasing farm profitability and economic stability.

## 6. Climate Resilience

The shading effect protects crops from extreme weather conditions such as heat waves, strong winds, and hail, making agriculture more resilient to climate change.

## 7. Biodiversity Benefits

Agrovoltaic fields can provide habitat for pollinators such as bees and insects, contributing to ecosystem conservation.

## Challenges of Agrovoltaics

Despite its benefits, agrovoltaics faces some challenges:

- High initial installation cost of solar panels
- Need for proper design to balance sunlight for crops and electricity generation
- Limited awareness among farmers
- Crop suitability varies depending on region and climate
- Maintenance of solar infrastructure

However, with technological advancements and government support, these challenges are gradually being addressed.

## Agrovoltaics in India

India has immense potential for agrovoltaic systems due to its high solar radiation and large agricultural land area. Government initiatives such as the PM-

KUSUM scheme promote the installation of solar panels on agricultural land and solar pumps for irrigation. Pilot projects across India have demonstrated the successful integration of crops such as leafy vegetables, pulses, and horticultural crops with solar power systems. Agrovoltaics can play an important role in achieving India's goals of renewable energy expansion, sustainable agriculture, and rural development.

## Future Prospects

Agrovoltaics is gaining global attention as a sustainable solution for food-energy challenges. With improvements in solar panel design, smart tracking systems, and crop management practices, agrovoltaic systems are expected to become more efficient and cost-effective. In the future, agrovoltaics may integrate with precision agriculture, smart irrigation systems, and digital farming technologies, further enhancing productivity and sustainability.

## Conclusion

Agrovoltaics is an innovative approach that integrates agriculture with solar energy production on the same land area. By allowing crops and solar panels to coexist, agrovoltaic systems improve land productivity, conserve water, enhance crop yields, and generate renewable energy. This dual-use technology provides economic benefits to farmers while supporting environmental sustainability and climate resilience. With increasing demand for both food and energy, agrovoltaics offers a promising pathway toward a more sustainable and resilient agricultural future.

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# Eco-Friendly Agricultural Structures Using Sustainable Construction Materials

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The construction sector is confronted with escalating environmental challenges owing to rapid urbanization, resource depletion, and rising carbon emissions. Agricultural structures, in particular, present a significant opportunity to embrace sustainable construction materials derived from agro-waste. This article reviews the application of key eco-friendly materials, including bamboo, rice husk ash, rice straw, sugarcane bagasse ash, and lignocellulosic panels, in the construction of green agricultural buildings. It synthesizes findings on the mechanical, thermal, and acoustic properties of these materials and discusses their potential to replace conventional construction inputs. The evidence collectively demonstrates that agro-waste-derived materials meet established building standards while delivering measurable environmental and economic benefits. Wider adoption of these materials in agricultural structures can substantially reduce the construction industry's carbon footprint and contribute to a circular economy.

## 1. Introduction

The global construction industry is widely recognized as one of the most resource-intensive and environmentally burdensome sectors in the world. Maraveas (2020) noted that the construction industry is the largest global consumer of raw materials, with the built environment accounting for 25% to 40% of the world's total greenhouse gas (GHG) emissions. According to the United Nations Environment Programme (UNEP), construction operations and building construction accounted for 36% of the global use of energy and up to 40% of carbon dioxide emissions in 2017 (Maraveas, 2020). These statistics underscore an urgent need for more sustainable building practices, particularly in sectors such as agriculture, where the scale of construction is extensive. Simultaneously, the agricultural sector generates enormous quantities of crop residue annually. In India alone, approximately 500 million tons of crop residue are generated every year, with the majority of rice and wheat residue being burned in open fields, causing severe air pollution and releasing substantial quantities of particulate matter and greenhouse gases (Singh et al., 2022). This dual challenge, namely the high environmental cost of

conventional construction and the problem of agro-waste disposal, has directed growing research interest toward the use of agricultural by-products as sustainable construction materials.

Sharma et al. (2026) reported a significant upward trend in global research on agricultural waste utilization in construction panels and boards, with annual publications rising sharply from 35 in 2017 to a peak of 113 in 2021. This growth reflects a growing global awareness of the need for sustainable materials and the increasing recognition of agricultural waste as a valuable resource. Against this backdrop, the present article reviews the science and application of eco-friendly materials derived from agro-waste for use in agricultural structures, tracing a coherent path from raw material properties through to structural performance and environmental benefits.

## 2. The Environmental Case for Agro-Waste-Based Construction Materials

The production of conventional construction materials, particularly cement, is among the most carbon-intensive industrial processes in the world. Endale et al. (2023) observed that the annual



production of cement exceeds 4.13 billion tons and accounts for approximately 8% of global carbon dioxide emissions. Furthermore, to align with the Paris climate agreement, annual emissions from the cement industry in the built environment must decrease by at least 16% by 2030 (Endale et al., 2023). These findings make an undeniable case for adopting supplementary cementitious materials derived from agro-waste.

Maraveas (2020) noted that the re-use of agricultural waste and by-products in the development of construction materials is a viable and tentative solution to tackle the dual challenge of high construction costs and the environmental problem of agro-waste disposal in landfills. The researcher further highlighted that the most common strategies used to manage such agro-waste, including dumping in landfills, incineration, and composting, generate severe environmental concerns, reinforcing the need for value-added use of these residues in construction. Sharma et al. (2026) corroborated this view, noting that dumping waste into landfills increases greenhouse gas emissions, and that waste management has become the most important environmental and natural resource preservation concern for governments worldwide.

Research shows that the construction industry was ranked as one of the least sustainable sectors due to its high dependence on non-renewable resources, with buildings accounting for 50% of water use, 45% to 50% of energy consumption, and 60% of building material consumption globally (Maraveas, 2020). By contrast, the use of agro-waste in developing building materials facilitates the reduction of pollution that is rife in the construction industry and also helps tackle the challenge of waste disposal, which troubles the agricultural processing industry. This convergence of benefits has driven rapid growth in the research and development of agro-waste construction materials over the past two decades.

### **3. Bamboo as a Structural Material in Agricultural Constructions**

Among the natural materials evaluated for sustainable construction, bamboo has emerged as one of the most promising due to its rapid growth rate, mechanical strength, and biodegradability. Adier et al. (2023) noted that the use of bamboo culms in the construction industry presents an environmental advantage because of the significant reduction in carbon dioxide generation compared to conventional structural materials. In comparison to timber, bamboo achieves maturity at a faster rate, typically taking only three to four years, while timber may require up to 12 years to develop adequate structural strength (Adier et al., 2023).

The mechanical properties of bamboo are particularly noteworthy. Adier et al. (2023) reported that bamboo possesses an impressive strength-to-weight ratio with excellent flexural ductility, exceeding that of wood by 3.06 times. In studies on compressive strength, five different bamboo species, including Moso, Guadua, Tali, Black Java, and Madake, were found to exhibit compressive strengths greater than 50 megapascals, which makes them suitable for construction use. In terms of tensile behavior, research by Adier et al. (2023) confirmed that *Bambusa tulda* has the strongest tensile strength of 226.28 megapascals among the tested bamboo species.

Madhushan et al. (2023) reinforced these findings, summarizing that bamboo is a natural biodegradable material used as a strength-bearing member in system works, formwork supporting stands, structural members in low-rise houses, props, framing, bridges, laminated flooring, facades, walls, roofs, and trusses. The researchers further found significant variability in bamboo's material and mechanical properties depending on growth conditions, location along the culm, geometric imperfections, and environmental conditions. This variability underscores the need for centralized



processing guidelines and standardized testing protocols to facilitate broader adoption of bamboo in modern agricultural construction (Madhushan et al., 2023).

Despite its strength, bamboo requires treatment to prevent biodegradation and ensure long-term durability. Adier et al. (2023) identified a range of natural and chemical treatment methods used by researchers, including drying, boiling, steaming, oil application, and impregnation with natural resin, all of which improve dimensional stability and resistance to moisture. The researchers also noted that treating bamboo using alkali at 60 degrees Celsius can increase the tensile strength of outer bamboo slivers by up to 86.6% compared to untreated bamboo. These developments in treatment technology position bamboo as a technically viable and environmentally responsible structural material for agricultural buildings.

#### **4. Agricultural Waste in Insulation, Masonry, and Wall Construction**

Beyond structural applications, agro-waste materials have demonstrated strong potential in the production of insulation, masonry bricks, and wall partition components for agricultural structures. Maraveas (2020) reviewed six categories of sustainable construction materials derived from agro-waste and found that in all cases the developed materials adhered to established building standards, indicating that agro-waste materials have the potential to replace conventional construction materials and achieve economic, environmental, and social sustainability in the long run. In the context of brick and masonry production, Maraveas (2020) reported that the addition of agricultural wastes, such as oat or barley husks, to clay brick formulations at concentrations between 5% and 10% produced bricks with acceptable compressive strengths ranging from 3.3 to 9.5 megapascals and total open porosity between 34% and 49%, making them suitable for green building applications. The researcher further

noted that researchers argued that the increase in porosity of these bricks led to a commensurate improvement in their lightweightness and thermal insulation properties, thereby becoming suitable for application in green buildings.

A particularly noteworthy development involves the use of rice straw in gypsum hollow-core blocks for partition walls. Singh et al. (2022) investigated various compositions of agro-waste-based gypsum samples and found that the addition of rice straw reduces the density of gypsum blocks, making them lightweight and suitable for non-load-bearing wall applications. The thermal conductivity of rice straw-added gypsum samples decreased from 0.2 to 0.11 watts per meter kelvin, indicating significantly improved thermal insulation performance. In terms of acoustic properties, the noise reduction coefficient (NRC) increased from 25% to 45% with increasing rice straw content, while the surface spread of flame and fire propagation index tests demonstrated good fire-resistant characteristics (Singh et al., 2022). These findings establish rice straw gypsum blocks as a multi-functional eco-friendly material highly suitable for agro-industrial buildings.

Sharma et al. (2026) further noted in their bibliometric review that various agricultural residues such as rice husk, sugarcane bagasse, and sawdust have attracted increasing global attention as raw materials for construction panels and boards owing to their renewability, low cost, and insulating properties. The review identified five thematic research clusters, one of which specifically addressed the evaluation of thermal and mechanical characteristics, including compressive strength and thermal conductivity, as critical dimensions of material performance assessment. This clustering of research priorities reflects the multidisciplinary nature of sustainable materials science, spanning civil engineering, material science, and environmental sustainability (Sharma et al., 2026).



## 5. Rice Husk Ash as a Supplementary Cementitious Material in Green Concrete

One of the most extensively researched applications of agro-waste in construction is the use of rice husk ash (RHA) as a supplementary cementitious material (SCM) in concrete. The global rice paddy field forecast for 2021/22 was 714.2 million tons, equating to approximately 142.84 million tons of rice husks, of which a significant fraction can be converted to reactive pozzolanic ash (Endale et al., 2023). Burning each ton of paddy yields approximately 0.2 tons of husks, and each ton of husks in turn yields about 0.05 tons of RHA containing significant amounts of amorphous silica, which contributes to pozzolanic activity in cement-based systems (Endale et al., 2023).

The pozzolanic property of RHA is determined by its amorphous silica content, specific surface area, and particle fineness, all of which can be improved through controlled combustion and grinding (Endale et al., 2023). Because RHA has a finer particle size than cement, RHA-blended concrete performs well in terms of fresh properties such as workability, consistency, and setting time. Regarding mechanical performance, Endale et al. (2023) found that the compressive, tensile, and flexural strengths of RHA-containing concrete increase with increasing RHA content up to a certain optimum level, owing to the role of amorphous silica in the pozzolanic reaction. The use of RHA also improved the durability properties of concrete, including water absorption, chloride resistance, corrosion resistance, and sulphate resistance.

Critically, Endale et al. (2023) concluded that RHA has the potential to replace cement by up to 10% to 20% without compromising concrete performance owing to its high pozzolanic properties. This finding has major implications for the construction of agricultural structures in rice-producing regions, where RHA is abundantly available as a low-cost by-product. The use of RHA

as a partial cement replacement not only reduces greenhouse gas emissions associated with cement production but also contributes to useful disposal of agricultural by-products and supports a circular economy in the construction industry (Endale et al., 2023). Maraveas (2020) similarly identified rice husk ash (RHA) as one of the most potent agro-waste solutions in sustainable construction, noting its widespread use across different product categories including green concrete and insulation materials.

## 6. Lignocellulosic Panels and Boards from Agricultural Waste

The production of construction panels and boards from lignocellulosic agricultural residues represents one of the fastest-growing areas of sustainable material science. Sharma et al. (2026) analyzed 887 publications from the Scopus database and reported a dramatic rise in research output in this field, with publications escalating from a low of 13 per year before 2009 to a peak of 113 in 2021. The review identified rice husk, sugarcane bagasse, sawdust, and other lignocellulosic wastes as the most frequently studied raw materials for panels and boards, attributing their popularity to renewability, low cost, and insulating properties. Sharma et al. (2026) noted that low-conductivity particleboards prepared from agricultural waste can be used for various purposes, including ceiling and wall insulation, providing energy efficiency benefits in agricultural storage facilities and farm buildings. The researchers also reported that the five identified clusters of research activity in this field covered a comprehensive range of material assessments, including modulus of rupture, modulus of elasticity, thermal conductivity, sound absorption, water absorption, and life cycle assessments. These evaluation dimensions indicate that the field has matured from primarily mechanical assessments toward holistic, environmentally informed appraisals of material performance.

Maraveas (2020) provided further detail on the specific performance of agro-waste particleboards,





noting that various crop residues including rice husk, sugarcane bagasse, and corn husks have been used to manufacture particleboards with thermal and acoustic properties suitable for building applications. The researcher drew attention to the widespread use of biomass-derived residues in thermal insulation, noting that materials such as hemp, straw, coconut, wood, and flax were highly popular in this category, while sisal, reed, grass, and pineapple were utilized less frequently. The thermal conductivity properties of these biomass residues, together with their heat capacity and thermal diffusivity, generated the highest research interest in the field of agro-waste insulation.

Building on these findings, Singh et al. (2022) highlighted the performance of rice straw-based composite boards, showing that composite materials produced from rice husk and recycled rubber granules demonstrate improved performance for impact sound insulation. The thermal conductivity of rice husk and cork granule-based composites was found to vary over the range of 0.0495 to 0.0798 watts per meter kelvin, with a maximum sound absorption coefficient of 95% at 1250 hertz, values comparable with other recycled building products (Singh et al., 2022). These performance characteristics confirm the suitability of agro-waste composite panels for partition walls, ceilings, and floor underlays in agricultural buildings.

## 7. Conclusion

The evidence reviewed across five bodies of research consistently demonstrates that eco-friendly construction materials derived from agricultural waste, including bamboo, rice husk ash, rice straw, sugarcane bagasse, and lignocellulosic panels, offer technically sound and environmentally sustainable alternatives to conventional building inputs. These materials satisfy established mechanical, thermal, and acoustic performance standards, confirming their viability for use in agricultural structures. The growing volume of research activity in this field, as

evidenced by publication trends spanning 2001 to 2025, reflects an accelerating global commitment to sustainable construction. Barriers such as variability in material properties, the absence of standardized processing guidelines, and limited large-scale market penetration remain to be fully addressed. Nevertheless, the cumulative scientific evidence makes a compelling case for mainstreaming agro-waste materials in agricultural construction, with the twin goals of reducing the construction industry's environmental impact and enabling value-added utilization of crop residues.

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# Teachable Machine: A Simple Artificial Intelligence Tool for Tomato Disease Detection

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Artificial Intelligence (AI) is rapidly transforming agriculture by helping farmers identify crop diseases at an early stage. Early diagnosis enables timely management, reduces yield losses, and minimizes unnecessary pesticide applications. Traditionally, developing AI models required programming knowledge and specialized software. Today, Google Teachable Machine has made AI accessible to everyone by allowing users to create image classification models without writing a single line of code. The platform enables users to collect images, train a model, test its performance, and export it for use in websites or mobile applications.

## Why Use Teachable Machine?

Teachable Machine is a free, browser-based machine learning platform developed by Google Creative Lab. It uses transfer learning to build image classification models quickly and efficiently. The platform is especially useful for agricultural universities, Krishi Vigyan Kendras (KVKs), extension workers, students, and researchers who wish to explore AI-based solutions without programming expertise. Models can be trained directly within a web browser and exported in TensorFlow Lite or TensorFlow.js formats for further deployment.

## Application in Tomato Disease Detection

Tomato is one of the most important vegetable crops cultivated worldwide. Diseases such as **Early Blight** and **Late Blight** can significantly reduce both yield and fruit quality. Accurate and timely identification of these diseases is therefore essential for effective crop management.

In this demonstration study, a no-code AI model was developed using Google Teachable Machine with field-collected tomato leaf images.

## Workflow

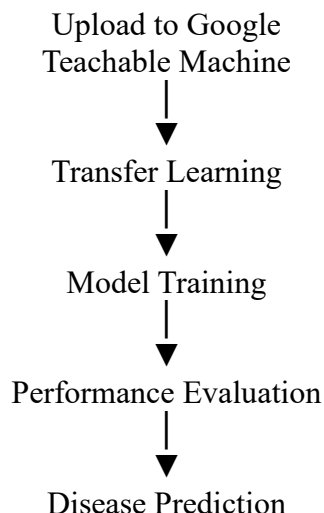
Field Image Collection  
↓  
Organize Images into Classes

↓  
Upload Images  
↓  
Google Teachable Machine  
↓  
Automatic Training  
↓  
Model Evaluation  
↓  
Prediction

## Complete Research Workflow

Tomato Crop  
↓  
Leaf Selection  
↓  
Image Capture  
↓  
Image Verification  
↓  
Healthy  
Early Blight  
Late Blight  
↓

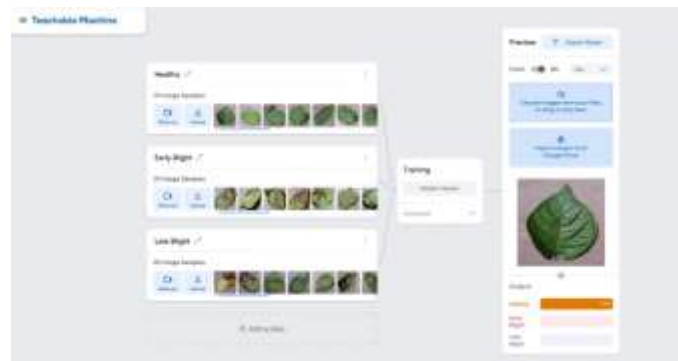
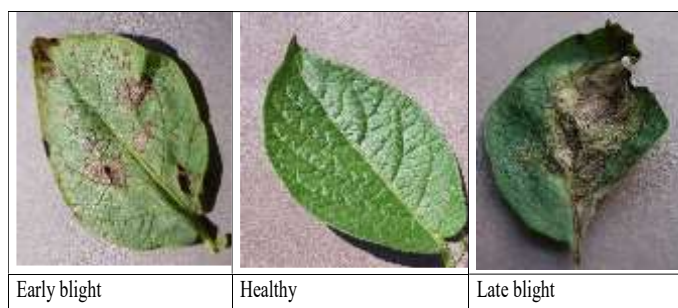




### Results

The trained model achieved an **overall evaluation accuracy of 96%** within the Teachable Machine environment. This demonstrates that even a simple no-code AI platform can effectively distinguish healthy tomato leaves from leaves affected by Early Blight and Late Blight in a pilot study.

Data Collection:



Healthy leaf detection by Teachable machine

### Advantages

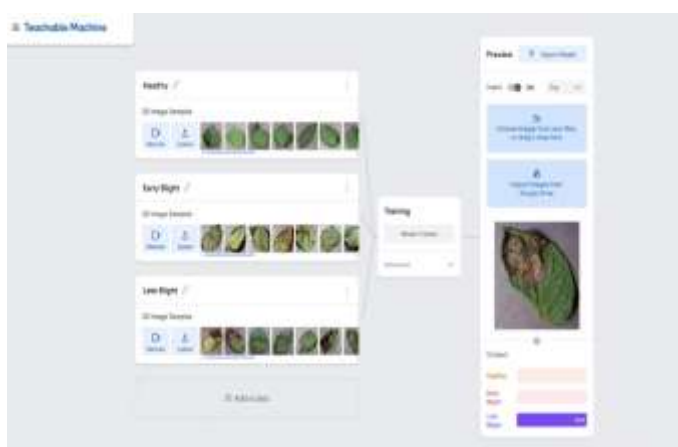
- No programming knowledge required.
- Free and browser-based platform.
- Quick model development.
- Supports transfer learning.
- Suitable for agricultural education and demonstrations.
- Can be integrated into websites and Android applications.
- Encourages digital agriculture and precision farming.

### Limitations

#### Limited Scalability

The platform is suitable for educational and small-scale research projects but may not be ideal for:

- Large commercial datasets
- Continuous model retraining
- Enterprise-scale deployment
- Cloud-based AI services
- Multi-user collaborative projects



Late blight Detection by Teachable machine



### Future Opportunities

The use of no-code artificial intelligence platforms offers exciting opportunities for Indian agriculture. Future developments may include:

- Mobile applications for on-field disease diagnosis.
- Integration with drone and IoT technologies.
- AI-based advisory systems for farmers.
- Real-time crop health monitoring.
- Digital extension services through Krishi Vigyan Kendras.

| Future Opportunity                 | Potential Benefit                               |
|------------------------------------|-------------------------------------------------|
| Smartphone-based disease diagnosis | Real-time field diagnosis by farmers            |
| Edge AI deployment                 | Offline and low-latency disease detection       |
| IoT integration                    | Improved prediction using environmental data    |
| Drone-based surveillance           | Large-scale crop monitoring                     |
| Explainable AI (XAI)               | Transparent and interpretable predictions       |
| Precision agriculture integration  | Site-specific disease management                |
| Region-specific models             | Improved accuracy under local conditions        |
| Multimodal AI                      | Enhanced diagnosis using multiple data sources  |
| Agricultural education             | Capacity building in AI and digital agriculture |
| Extension services                 | Farmer-friendly decision                        |

|                                        |                                                 |
|----------------------------------------|-------------------------------------------------|
|                                        | support                                         |
| Cloud-based systems                    | Centralized disease monitoring and analytics    |
| Continual learning                     | Automatic model improvement over time           |
| National digital agriculture platforms | Large-scale disease surveillance                |
| Sustainable agriculture                | Reduced pesticide use and improved productivity |

### Conclusion

Google Teachable Machine provides an easy and practical entry point into artificial intelligence for agriculture. By enabling users to create image classification models without programming, it empowers researchers, students, and extension professionals to explore innovative solutions for crop disease diagnosis. Although larger datasets are needed for widespread deployment, the technology demonstrates significant potential to support precision agriculture and strengthen digital advisory services for farmers.

The future of Google Teachable Machine in plant disease detection lies in its integration with emerging technologies such as Edge AI, Explainable AI, IoT, UAVs, cloud computing, and precision agriculture platforms. While the platform is currently most suitable for education, rapid prototyping, and small-scale applications, these technological advancements could significantly expand its role in practical agricultural decision support. Developing field-validated, scalable, and region-specific no-code AI solutions will be crucial for enhancing disease diagnosis, supporting agricultural extension services, and promoting sustainable crop production.



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# Citation Context Analysis: Looking Beyond Citation Counts

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Citation Context Analysis (CCA) is a modern bibliometric approach that examines the textual context surrounding citations to understand their purpose and significance. Unlike traditional citation analysis, it focuses on why and how a reference is cited rather than simply counting citations. By identifying citation functions and contexts, CCA provides a deeper understanding of scholarly communication and supports more accurate research evaluation.

## Introduction

Citation Context Analysis (CCA) is a bibliometric approach that examines the text surrounding an in-text citation to understand why and how a source has been cited, rather than simply counting the number of citations it has received. It helps identify the purpose and role of a citation, such as providing background, supporting a claim, describing a method, or criticizing previous research (Tahamtan & Bornmann, 2019).

## Importance of Citation Context Analysis

- **Provides deeper insights into research impact:** Citation Context Analysis evaluates not only how often a publication is cited but also why it is cited, offering a more meaningful assessment of scientific influence (Bornmann & Daniel, 2008).
- **Identifies the purpose of citations:** It distinguishes whether a citation is used for background information, supporting evidence, methodology, comparison or criticism, thereby clarifying the role of the cited work (Tahamtan & Bornmann, 2019).
- **Improves literature reviews:** By revealing how previous studies are used in new research, Citation Context Analysis helps researchers identify

foundational studies, research gaps and emerging trends (Tahamtan & Bornmann, 2019).

- **Enhances research evaluation:** It complements traditional citation metrics by considering the context and significance of citations rather than relying solely on citation counts (Bornmann & Daniel, 2008).
- **Supports Artificial Intelligence and Natural Language Processing (NLP):** Citation Context Analysis is widely used to develop automated systems that classify citation functions, improve academic search engines and recommend relevant scientific literature (Teufel et.al., 2006).
- **Facilitates evidence-based decision-making:** Funding agencies, policymakers, and research institutions can use Citation Context Analysis to identify influential and high-quality research for strategic planning and evaluation (Tahamtan & Bornmann, 2019).

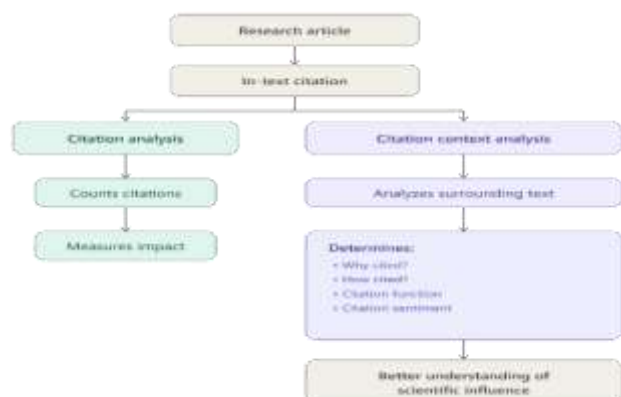
**Table 1. Difference Between Citation Analysis and Citation Context Analysis**

| Aspect     | Citation Analysis                       | Citation Context Analysis (CCA)                                   |
|------------|-----------------------------------------|-------------------------------------------------------------------|
| Definition | Measures the impact of a publication by | Examines the textual context surrounding a citation to understand |



|                 |                                                           |                                                                                                                        |
|-----------------|-----------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------|
|                 | counting the number of times it is cited.                 | why and how it is used.                                                                                                |
| <b>Focus</b>    | Citation counts and citation-based indicators.            | Citation purpose, function, sentiment, and significance.                                                               |
| <b>Approach</b> | Quantitative.                                             | Qualitative and quantitative (text analysis).                                                                          |
| <b>Answers</b>  | "How many times has this work been cited?"                | "Why and in what context has this work been cited?"                                                                    |
| <b>Purpose</b>  | Evaluates research impact and productivity.               | Explains the intellectual influence and role of citations in scholarly communication.                                  |
| <b>Example</b>  | A paper cited 500 times is considered highly influential. | A paper may be cited to support, compare, criticize, or describe a methodology, revealing the nature of its influence. |

The distinction between citation analysis and citation context analysis is well established in bibliometric research. While traditional citation analysis focuses on the number of citations a publication receives, citation context analysis investigates the textual context in which citations appear to determine their purpose, function and meaning (Bornmann & Daniel, 2008; Tahamtan & Bornmann, 2019).



## Common Functions of Citations

Although several classification frameworks have been proposed, most citations can be grouped into the following categories.

### 1. Background Citation

Used to introduce a topic or provide general information.

*Example: "Climate change poses significant challenges to global food security."*

These are the most common citations in any paper's introduction, but also the least informative about a source's actual influence, they signal relevance to a topic rather than genuine engagement with its findings.

### 2. Conceptual Citation

Used to cite theories, models, frameworks or definitions that underpin the study.

Conceptual citations tend to mark a source as foundational within a field, since theories and frameworks are typically reused far more often than any single empirical result.

### 3. Methodological Citation

Used to acknowledge an analytical method, protocol, questionnaire or statistical procedure adopted from previous research.

*Example: "The data were analysed following the procedure described by..."*

Here the author is borrowing a tool rather than an idea, which means a heavily cited methods paper can have enormous practical reach while attracting little genuine theoretical debate.

### 4. Supporting Citation

Used when previous findings agree with or strengthen the author's argument.



*Example: "Our results are consistent with earlier observations reported by..."*

Supporting citations are often assumed to be the default meaning of any citation, but they are only one function among several, distinguishing them from neutral background mentions remains one of the harder tasks for automated classifiers.

## 5. Contrasting Citation

Used to highlight disagreement, limitations, or contradictory findings.

*Example: "In contrast to previous studies, no significant effect was observed."*

This is the category raw citation counts hide most damagingly: a heavily contrasted paper can look just as "successful" on a citation chart as one that is uniformly praised, even though the two indicate very different scientific standing.

## 6. Persuasive Citation

Used strategically, to lend authority or credibility to a claim rather than to engage substantively with the cited work's content.

*Example: "As numerous scholars have shown, this phenomenon is well established."*

Persuasive citations are not necessarily dishonest, but they reveal that citing behavior is shaped by rhetorical convention and disciplinary norms as much as by genuine intellectual debt.

These categories illustrate that citations perform multiple rhetorical and scientific functions rather than merely acknowledging previous work (Teufel et al., 2006).

## Applications in Research Evaluation

The practical payoff of all this technical work is a more defensible approach to research evaluation. Citation context data has been used to:

- Distinguish papers that are genuinely foundational to a field from those that are merely popular, by separating conceptual and methodological citations from passing background mentions.
- Detect early signs of controversy or disputed findings that raw citation counts would leave completely invisible, since a heavily contested paper and a heavily praised one can post identical numbers.
- Enrich literature reviews by clarifying how studies actually relate to one another, rather than simply listing who cited whom in a bibliography.
- Improve citation-based recommendation and academic search systems, by surfacing sources that are conceptually central rather than merely frequently mentioned.
- Supplement peer review and funding decisions with a qualitative layer that pure metrics cannot provide, giving evaluators a sense of how a body of work has actually been received.

Major citation databases have started to take this seriously at an infrastructural level: citation context data is now being systematically incorporated into large-scale platforms, moving this kind of analysis out of small hand-coded studies and into everyday research evaluation.

## Conclusion

Citation Context Analysis offers a more meaningful way to evaluate scientific literature by examining the context and purpose of citations. It complements traditional citation metrics by revealing the true influence of research. With the growing use of Artificial Intelligence and Natural Language Processing, CCA is becoming an essential tool for improving research assessment and scholarly communication.

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# E-NAM and Digital Agricultural Marketing: Adoption Gaps in Hill States

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The National Agriculture Market (e-NAM) has grown into one of India's most ambitious attempts to digitally unify a historically fragmented mandi system. Since its 2016 launch, the platform has expanded to link more than 1,650 wholesale markets across the country and has registered well over a crore farmers. Yet this growth has been strikingly uneven across geography and crop type. Hill states such as Himachal Pradesh, characterised by fragmented landholdings, difficult terrain and horticulture dominated cropping systems, have consistently lagged behind the plains in mandi integration and farmer participation. This article examines the structural and operational reasons for this adoption gap, using Himachal Pradesh as an illustrative case, and reviews emerging digital-marketing responses such as private-sector digital mandi pilots for apple procurement. It concludes with policy directions tailored to hill agriculture, arguing that digital market reform needs deliberate adaptation rather than uniform rollout.

## Introduction

e-NAM was launched in April 2016 as a pan-India electronic trading portal that networks existing Agricultural Produce Market Committee (APMC) mandis onto a common online platform, implemented by the Small Farmers' Agribusiness Consortium under the Ministry of Agriculture and Farmers' Welfare. Its core promise was to replace fragmented, licence-bound local trading with a single-licence, transparent e-auction system that widens the pool of buyers available to any farmer at any integrated mandi, thereby improving price discovery and reducing dependence on local intermediaries.

By late February 2026, the platform had integrated 1,656 mandis spread across 23 states and 4 union territories, with more than 1.80 crore farmers, 2.72 lakh traders and 4,724 Farmer Producer Organisations (FPOs) registered on it. Cumulative trade since inception had crossed 13.22 crore metric tonnes, valued at approximately ₹4.82 lakh crore (PIB, 2026). These are impressive numbers at the

aggregate level. Independent assessments, however, suggest that e-NAM's share of total APMC trade nationally remained modest through the mid-2020s, indicating that even in well-connected plains markets, actual online trading intensity trails registration numbers by a wide margin. In hill states, this gap between formal integration and functional use is considerably wider still.

## Himachal Pradesh's Marketing Infrastructure

Agricultural marketing in Himachal Pradesh is regulated through the Himachal Pradesh Agricultural Marketing Board, under which 10 main APMC markets and 61 sub-markets currently operate across the state's districts (HP Agricultural Marketing Board, n.d.). In the platform's early rollout years, integration progress in the hill states was visibly slower than in the plains: as of September 2016, only two mandis in Himachal Pradesh had been enrolled on e-NAM, compared with 44 in Telangana and 31 in Haryana in the same reporting window (The Tribune, 2016).





This is not incidental. Himachal Pradesh's farm economy is dominated by small, scattered landholdings and a high dependence on perishable, seasonal horticultural produce. The state's apple economy alone, which spans roughly one lakh hectares, about half of its total fruit-growing area, produces around 5.5 lakh metric tonnes annually and contributes upward of ₹6,000 crore to the local economy (The News Mill, 2026). Grain and other non-perishable commodities, for which e-NAM's design (deferred delivery, standardised grading, longer holding windows) works reasonably well, form a much smaller share of marketable surplus in the hills. Perishables instead require instantaneous quality assessment, cold-chain-linked logistics and rapid payment settlement, features that the assaying and payment infrastructure at many remote hill mandis is not yet equipped to deliver at scale.

### **Why Adoption Lags: Structural Barriers**

Several interlinked factors explain the slower uptake of digital marketing tools in hill agriculture. Terrain and connectivity constraints mean that remote mandis in hill districts often contend with inconsistent internet connectivity, which disrupts real-time bidding, the central mechanism through which e-NAM is meant to deliver price gains.

Trader participation also remains thin. e-NAM's value proposition rests on drawing a wider pool of buyers into competitive bidding at each mandi. In small hill mandis, the number of registered traders is limited, so in practice the same locally known traders continue to bid, and the platform functions more as a digital record-keeping tool than as a genuine price-discovery mechanism.

Grading and assaying infrastructure poses a further constraint. Horticultural produce requires specialised grading, based on size, colour, blemish and ripeness, that differs substantially from the commodity-standard grading e-NAM was originally built around for grains and pulses. Quality-

certification labs and grading equipment suited to fruit and off-season vegetables remain scarce at hill mandis.

Because landholdings are fragmented, an individual hill farmer's tradable surplus at any one time is often too small to justify independent online engagement, even where digital literacy is not itself a barrier. Finally, payment and settlement frictions arise because e-NAM transactions are designed around electronic payment settlement directly into farmers' bank accounts; where banking penetration and account access in remote blocks remain uneven, this can introduce delays that undercut the platform's promise of prompt payment.

### **Emerging Responses: Digital Mandis and Aggregator-Led Models**

Recent private-sector initiatives suggest a possible way forward. Adani Agri Fresh piloted a digital mandi model for apple procurement in Himachal Pradesh, trading close to 1,000 tonnes in its first year, and has since announced plans to scale up Digital Mandis across its controlled-atmosphere storage units in Rampur, Rohru and Sainj (The News Mill, 2026). The model links digital price discovery directly to existing cold-storage and aggregation infrastructure, rather than expecting individual farmers to trade independently online.

This pattern was echoed at the 7th Annual Apple Conclave held in Theog, where industry stakeholders and scientists emphasised strengthening market linkages and accelerating adoption of digital platforms such as e-mandis alongside improvements in orchard management and planting material. The broader lesson is that in hill terrain, aggregator- or FPO-led digital linkages, where produce is pooled before it is traded online, may prove more workable in the near term than an open, farmer-to-platform bidding model designed with plains-style commodity markets in mind.



## Policy Directions

Digital marketing efforts in hill states should prioritise FPO-level aggregation before individual farmer onboarding, directly addressing the problem of thin marketable surplus per farmer. Mobile and offline-sync-capable bidding applications, which can queue transactions during connectivity outages and sync when networks are restored, would reduce the operational risk that unreliable connectivity currently poses to real-time bidding. Investment in crop-specific grading and assaying infrastructure for horticultural produce at hill mandis, potentially through public-private partnerships modelled on the Adani digital mandi experience, would help extend quality-based price discovery beyond a handful of pilot sites. Targeted campaigns to widen trader licensing and participation specific to horticultural produce could help hill mandis draw a genuinely larger buyer pool rather than simply digitising an unchanged set of local traders. Finally, e-NAM integration would benefit from being planned alongside existing state infrastructure programmes, such as the World Bank-funded Himachal Pradesh Horticulture Development Project and the JICA-funded Crop Diversification Promotion Project, so that cold-chain, road and market-yard investments converge with digital rollout rather than proceeding on separate tracks.

## Conclusion

e-NAM's national scale-up is a genuine institutional achievement, but its aggregate numbers mask significant regional unevenness. For a hill state like Himachal Pradesh, where landholdings are

fragmented, produce is dominated by perishable horticulture, and market infrastructure is thinner than in the plains, digital marketing reform needs deliberate adaptation rather than uniform extension. Aggregator-led digital linkages, horticulture-specific grading investment and connectivity-resilient trading tools are likely to matter more for hill farmers than simply adding more mandis to the national count.

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# Can Sustainable Finance Drive India's Viksit Bharat Vision?

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India's aspiration to become a developed nation by 2047 under the *Viksit Bharat* vision is one of the most ambitious development goals in its history. Achieving this vision will require more than sustained economic growth—it will demand a financial system that supports long-term, inclusive, and environmentally responsible development. This is where sustainable finance assumes strategic importance.

Sustainable finance refers to financial decisions that incorporate environmental, social, and governance (ESG) considerations alongside economic returns. Rather than viewing sustainability as a constraint on growth, it recognizes that responsible investments create long-term value by reducing risks, enhancing resilience, and promoting inclusive development. As global investors increasingly prioritize sustainability, countries with robust sustainable finance frameworks are likely to attract greater investment and strengthen their economic competitiveness.

India has already taken meaningful steps in this direction. The introduction of the Business Responsibility and Sustainability Reporting (BRSR) framework, the growth of green bonds, the expansion of renewable energy financing, and the increasing adoption of ESG practices by Indian companies reflect a gradual shift towards responsible finance. These initiatives are helping businesses improve transparency, strengthen governance, and align with global sustainability expectations.

However, important challenges remain. Concerns over greenwashing, inconsistent ESG disclosures, limited assurance mechanisms, and the relatively high cost of sustainable investments continue to affect investor confidence. Small and medium-sized enterprises often lack the financial and technical capacity to implement sustainability practices effectively. Addressing these challenges requires stronger regulatory support, improved

disclosure standards, credible assurance frameworks, and greater awareness among businesses and investors.

Sustainable finance is not merely an environmental agenda; it is an economic strategy that can accelerate India's development trajectory. By directing capital towards renewable energy, sustainable infrastructure, climate-resilient agriculture, clean technologies, and socially responsible enterprises, India can generate employment, stimulate innovation, enhance energy security, and strengthen long-term economic resilience.

The journey towards *Viksit Bharat* will ultimately depend on the quality as well as the pace of economic growth. Sustainable finance offers a pathway to ensure that development remains competitive, inclusive, and future-ready. If India continues to strengthen its sustainable finance ecosystem through sound regulation, transparent governance, and responsible investment practices, it can transform sustainability from a compliance requirement into a powerful driver of national prosperity. In doing so, sustainable finance can become one of the defining pillars of India's journey towards becoming a developed nation by 2047.

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# Exploring the world of Indian black carpenter ant, *Camponotus compressus*

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The Indian black carpenter ant (*Camponotus compressus*) is a highly adaptable, socially complex species widely distributed across tropical Asia. Structured into distinct castes queens, workers, and soldiers this nocturnal, omnivorous ant coordinates through sophisticated behaviors like trophallaxis and chemical alarm signaling. Ecologically, it plays a vital role in soil aeration, nutrient recycling, and natural pest control, while maintaining mutualistic, honeydew-seeking relationships with sap-sucking insects. However, its resilience allows it to thrive in urban environments, where excavating moist wood can cause structural damage. Understanding this superorganism is essential for balancing its ecological benefits with effective urban management.

## Introduction

*Camponotus compressus*, commonly known as the Indian black carpenter ant, is a large, ecologically significant ant species recognizable by its shiny black body and powerful mandibles. Widely distributed across South Asia, this resilient species is renowned for its highly organized social structure and complex colony dynamics. The species operates as a cohesive superorganism divided into distinct castes, including a reproductive queen, sterile workers, and formidable soldiers, each performing specialized roles to ensure colony survival. As primarily nocturnal foragers, these ants exhibit sophisticated behavioral adaptations, such as trophallaxis and advanced chemical communication. Beyond their fascinating biology, they play a vital environmental role by contributing significantly to soil aeration, organic decomposition, and the biological control of agricultural pests, maintaining the delicate balance of both natural and human-modified ecosystems.

## Distribution and Host Range

*Camponotus compressus* is widely distributed across tropical and subtropical regions of Asia. This species

is predominantly found in countries such as India, Sri Lanka, Bangladesh, Nepal, Pakistan, and parts of Myanmar. Due to its remarkable adaptability, the species thrives in a wide variety of habitats including forests, agricultural lands, gardens, plantations, urban settlements, and roadside environments. These ants prefer warm climatic conditions with moderate moisture and are commonly observed nesting in tree trunks, dead wood, soil cavities, wall crevices, and wooden structures.

The host range of *Camponotus compressus* is highly diverse because of its omnivorous feeding behavior and ecological interactions. The ants are frequently associated with crop plants and trees such as mango (*Mangifera indica*), coconut (*Cocos nucifera*), neem (*Azadirachta indica*), banana (*Musa* spp.), sugarcane (*Saccharum officinarum*), and various flowering garden plants. They maintain mutualistic relationships with sap-sucking insects such as aphids, mealybugs, and scale insects, from which they obtain honeydew as a carbohydrate-rich food source. In return, the ants protect these insects from predators and parasitoids. This wide host association enables the species to survive



successfully in both natural and human-modified ecosystems.

### Life Cycle

The life cycle of *Camponotus compressus* is characterized by complete metamorphosis and consists of four developmental stages: egg, larva, pupa, and adult. The process begins when the queen lays approximately 15 to 20 oval-shaped white eggs inside the protected chambers of the nest. These eggs are carefully tended by worker ants, which maintain proper temperature, humidity, and cleanliness to ensure successful development. After a few days, the eggs hatch into larvae, which are soft-bodied, legless, and entirely dependent on workers for food and care. The larvae are nourished through trophallaxis, a process in which workers transfer liquid food directly from their mouths.

As the larvae grow, they undergo several molts before transforming into pupae. During the pupal stage, major internal and external changes occur as the insect develops adult characteristics such as legs, antennae, compound eyes, and wings (in reproductive individuals). In some cases, the pupae are enclosed within protective cocoons. After completing metamorphosis, fully developed adult ants emerge from the pupal stage. Depending on the colony's needs, these adults may become workers, soldiers, or reproductive males and queens. Worker ants immediately begin performing colony tasks such as nest maintenance, brood care, and foraging, while reproductive individuals participate in nuptial flights to establish new colonies. This highly organized life cycle ensures the continuous growth, survival, and expansion of the ant colony.

### Behavior and Habitat

The Indian black carpenter ant exhibits highly organized social behavior characterized by a clear division of labor among different castes. Workers are responsible for foraging, nest maintenance, and brood care, while soldiers defend the colony against

threats. The queen's primary role is reproduction, ensuring the continuity of the colony. These ants are generally nocturnal, preferring to forage during cooler hours to avoid predators and environmental stress. Foragers generally emerge between sunset and midnight, with peak numbers being recorded between 20:00 and 24:00 hours (8 PM to 12 AM). Their nests are typically located in moist and sheltered environments such as decaying wood, tree cavities, and underground tunnels, providing protection and stable conditions for colony development.

### Eating Habits

Feeding behavior in *Camponotus compressus* is both diverse and highly coordinated. These ants are omnivorous, consuming a wide variety of food sources including plant nectar, honeydew secreted by aphids, and small insects. A key feature of their feeding system is trophallaxis, a process in which food is exchanged mouth-to-mouth among colony members. This ensures efficient distribution of nutrients throughout the colony, from foragers to workers and larvae. Sugary substances serve as the primary energy source, while proteins obtained from insects are essential for growth and development, particularly in the larval stage.

### Types of Interaction

*Camponotus compressus* engages in multiple ecological interactions that influence its environment. One of the most notable is mutualism with aphids, where ants protect aphids from predators in exchange for honeydew. They also exhibit commensal relationships by improving soil conditions through their nesting activities, indirectly benefiting plant growth. As predators, they help control populations of small insects, contributing to natural pest management.

The dual roles of *Camponotus compressus* as both a predator and a supporter of aphids are not actually contradictory; they are complementary





strategies used by the colony to balance its nutritional needs for both carbohydrates and protein. This complex relationship, known as trophobiosis, involves specific behavioral shifts based on the colony's current demands for mutualism and predation.

### Ecosystem Impact

The ecological contributions of the Indian black carpenter ant are significant and multifaceted. Their tunneling activities enhance soil aeration, allowing better water infiltration and root growth. By breaking down organic matter, they facilitate nutrient recycling and improve soil fertility. Their role as predators helps regulate pest populations, making them beneficial in agricultural systems. Furthermore, their occasional involvement in seed dispersal contributes to plant diversity and ecosystem sustainability. Overall, their presence supports the balance and productivity of both natural and managed ecosystems.

### Alarm Communication

Communication within *Camponotus compressus* colonies is highly sophisticated and essential for survival. When threatened, these ants release chemical signals known as alarm pheromones which are not a single chemical but a blend of compounds (including formic acid, n-undecane, and 4,8-dimethyl-7-nonen-2-one) released from different glands to trigger specific defensive behaviors. This rapidly alerts other colony members to danger and triggers coordinated defensive or escape responses. In addition to chemical communication, they also use mechanical signals such as vibrations and physical contact to transmit information. These communication systems ensure that the colony can respond quickly and effectively to predators, environmental disturbances, and other threats.

### Urban Habitat Characteristics

In urban environments, *Camponotus compressus* demonstrates remarkable adaptability. It often nests in wooden structures, furniture, walls, and other man-made materials, especially in areas with high moisture levels. While these ants play beneficial roles in natural ecosystems, their presence in buildings can lead to structural damage over time. Urban habitats also influence their foraging behavior, as they exploit readily available food sources such as kitchen waste and sugary substances. Despite these challenges, their ability to thrive in human-dominated landscapes highlights their resilience and ecological versatility.

### Colony Organization and Caste System

The colony of *Camponotus compressus* is a highly organized social unit structured into different castes, each with specific roles that ensure the survival and efficiency of the colony. The queen is the reproductive center, responsible for laying thousands of eggs during her lifetime. Worker ants, which are sterile females, perform multiple tasks such as foraging for food, caring for the brood, and maintaining the nest. In addition, larger workers known as soldiers possess stronger mandibles and play a key role in defending the colony from predators and rival ants. This division of labor enhances productivity and allows the colony to function as a coordinated superorganism.

### Nesting Behavior

Unlike termites, carpenter ants do not consume wood but excavate it to create intricate nesting galleries. *Camponotus compressus* prefers moist or decaying wood, which is easier to carve and provides a suitable microenvironment for colony development. Their nests may consist of interconnected chambers used for brood rearing, food storage, and resting. In some cases, colonies may establish satellite nests in addition to the main nest, especially when the colony size increases. This nesting behavior helps in



resource distribution and reduces overcrowding within the colony (Tschinkel, 2005).

### Conclusion

The Indian black carpenter ant (*Camponotus compressus*) is far more than a common insect; it is a highly evolved social organism that plays a critical role in both natural and human-influenced ecosystems. Its advanced colony structure, efficient resource management, and diverse ecological interactions highlight its importance in maintaining environmental balance. While it offers numerous benefits such as soil improvement and pest control, its adaptability to urban environments can sometimes lead to conflicts with humans. A deeper understanding of this species not only aids in effective management but also provides valuable insights into the complexity of social insect life.

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# Vertical Farming – A Way to Sustainable Agriculture

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As Global Urbanization and climate change threaten traditional agriculture, vertical farming offers a sustainable solution for food security. This explores the potential of multi-layer, indoor crop production using controlled environment agriculture (CEA). By implementing technologies such as hydroponics (growing plants in water), aeroponics, aquaponics, and LED lighting, vertical farms decouple agriculture from land and climate constraints.

## Introduction

Agriculture plays an important role in the Indian economy. Agriculture supports more than 70% of rural families. Agriculture is a major sector of the Indian economy, accounting for approximately 17% of total GDP and employing more than 60% of the workforce. India is the most populous country. Feeding this expanding population will undoubtedly become a challenge as time goes on. In addition, current and historical agricultural practices are extremely detrimental to the environment. Furthermore, industrialization is rapidly rising, putting many arable lands at jeopardy. To overcome this, vertical farming is the solution.

## History of Vertical Farming

Vertical Farming, in its modern form, began to develop in the late 20<sup>th</sup> and early 21<sup>st</sup> centuries, but its initial steps can be tracked back over a hundred years. The foundation of modern vertical farming can be linked to the early 20<sup>th</sup> century. A key moment in the history of vertical farming occurred in 1915, when engineer and inventor Gilbert Ellis Bailey presented the idea of urban farms located on building rooftops in his work *The Vertical Farm: A New way to Grow food*. Although the idea was not realized at the time, it entered broader discussions about the future of agriculture in urban environments. Bailey proposed that, in densely populated cities, vertical

space could become a crucial resource for growing food.

In the Second half of the 20<sup>th</sup> century, it became increasingly clear that the global rise in population, accelerated urbanization, and climate change would pose serious challenges to traditional agriculture methods. With the growth of urban areas, there was growing need for alternative food population methods, laying the groundwork for a more serious consideration of vertical farming as a sustainable solution for the future of agriculture.

## Principles of Vertical Farming

- **Controlled Environment Agriculture (CEA):** Crops grown indoors with precise control of light, temperature, humidity, and CO<sub>2</sub>.
- **Stacked growing systems:** plants arranged in vertical layers (or towers) to maximize yield per square foot of floor space.
- **Soilless growing methods:** Typically, hydroponics (nutrient-rich water), aeroponics (nutrient mist on roots), or aquaponics (fish waste as nutrients).
- **Artificial lighting:** LEDs tuned to specific light wavelengths that plants need, replacing sunlight.
- **Closed-loop resource use:** Water and nutrients are recirculated, compared to field farming the waste resources are used efficiently in the vertical farming



- **Proximity to consumers:** Often built in or near cities, shortening the supply chain from farm to consumers' table.

### Based on the structures type in vertical farming

**Mixed-use sky scrapers:** Mixed-use skyscrapers were proposed and built by architect Ken Yeang. The Ken Yeang proposes that instead of hermetically sealed mass-produced agriculture, plant life should be cultivated within open air, mixed-use skyscrapers for climate control and consumption. This version of vertical farming is based upon personal or community use rather than the wholesale production and distribution plant life that aspires to feed an entire city. It thus requires less of an initial investment than Despommier's "vertical farm". However, neither Despommier nor yeang are the conceptual originators, nor is Yeang the inventor of vertical farming in skyscrapers.



Fig 2. Despommier's Skyscrapers

**Stackable shipping containers:** Several companies have brought forth the concept of stacking recycled shipping containers in urban settings. Brighter side consulting has created off grid container system Freight Farms produces a "leafy green machine" that is a complete farm-to-table system outfitted with vertical hydroponics, LED lighting and intuitive climate controls built within a 12m×2.4m shipping container. Podponics has built a large-scale vertical farm in Atlanta consisting of over 100 stacked "growpods". A similar farm is currently under construction in Oman.



Fig 1. Structure of vertical farming

**Despommier's Skyscrapers:** Proposed by Dr. Dickson Despommier in 1999 at Columbia University. Promotes growing crops in multi-storey buildings (vertical farms). In this type uses controlled indoor environments for year-round production and requires less land and water while reducing environmental pollution. It can be established near cities, lowering transportation costs and providing fresh produce. It supports the sustainable agriculture through efficient resource use and commercial-scale food production.



Fig 3. Stackle shipping containers

### Types of vertical farming

**Hydroponics:** Hydroponics is a soilless farming method that uses a water-based nutrient solution to nourish plant roots. The plants are supported by inert mediums like clay pellets or perlite. Hydroponics





conserves water, minimizes soil-borne diseases, and boosts crop yields with faster growth rates.

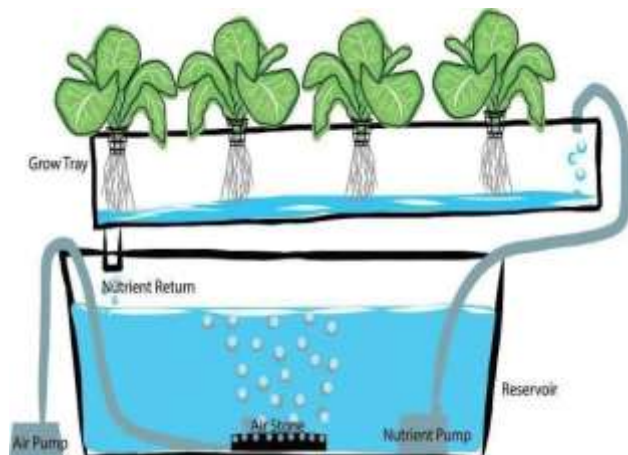


Fig 4. Crops grown under hydroponics system

**Aeroponics:** Aeroponics suspends plant roots in the air and mists them with a nutrient rich solution. It provides superior oxygenation, faster plant development, and precise environmental control for optimal crop growth.

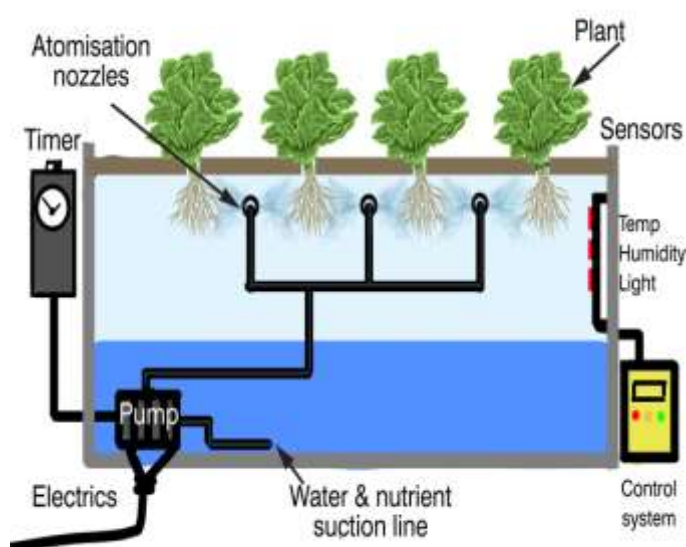


Fig 4. Crops grown under aeroponics

**Aquaponics:** Aquaponics integrates hydroponics and aquaculture, creating a closed-loop system where fish waste becomes nutrient-rich fertilizer for plants, and plants purify the water for fish. It maximizes resource efficiency and supports sustainable food production in various environments.

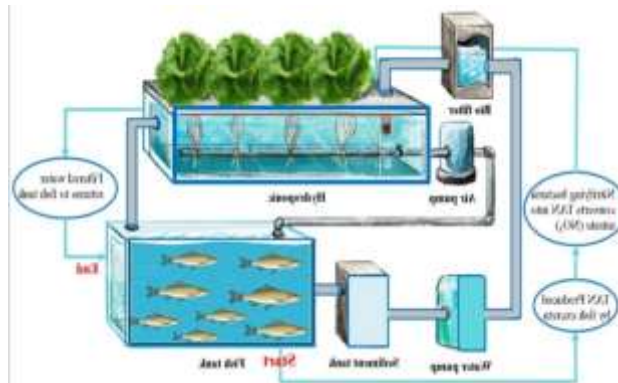


Fig 5. Integration aquaculture and hydroponics system

### Challenges in vertical farming

- **Massive energy use:** Due to lack of sunlight availability, the artificial light energy was used in vertical farming that will increase the high energy use, and reduce the profit cost to the farmers.
- **High upfront capital:** Building and equipping a vertical farm is more expensive compared to traditional agriculture.
- **Limited crops cultivation:** vertical farming is suitable for fast growing crops like lettuce, herbs, microgreens, fruiting vegetables and berries, and staple crops like (wheat, rice, maize) aren't practically growing in vertical farming yet due to space and light needs.
- **Technical complexity:** Requires expertise in engineering, plant science, and automation, and not required only in farming knowledge.
- **Pollination:** No Natural pollinators in vertical farming, So Some crops need manual or mechanical pollination.

### Advantages in vertical farming

- a. Grow food 24 hours a day, 365 days a year
- b. Protect crops from unpredictable and harmful weather
- c. Re-use of water collected from the indoor environment





- d. Provide jobs for residents/communities
- e. Minimize use of pesticides/fertilizers/herbicides
- f. Drastic reduction and dependance on fossil fuels
- g. Prevent crop loss from storage /shipping/long transportation
- h. Water saving up to 90%

### Disadvantages in vertical farming:

- a. An expert is needed to create a vertical farming project
- b. High initial costs
- c. High Power Consumption
- d. Dependance on the constant availability of water and electricity
- e. High labor costs
- f. Expensive maintenance
- g. No recycling infrastructure
- h. Reduction of jobs in rural areas

### Conclusion

Vertical farming offers a promising path toward more sustainable and resilient food production, especially as urban populations grow and arable land becomes scarer. By stacking crops in controlled indoor environments, it dramatically reduces water use,

eliminates the need for pesticides, and shortens the distance food travels from farm to consumer table. However, high upfront costs and significant energy demands remain real barriers to widespread adoption. As technology advances and renewable energy becomes more accessible, vertical farming has the potential to play a key role in feeding growing cities while easing pressure on traditional farmland.

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# Microplastic–Nutrient Interactions in the Fish Gastrointestinal Tract Mechanisms, Consequences and Nutritional Mitigation in Aquaculture

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Microplastic (MP) contamination has become an emerging challenge in aquaculture, affecting nutrient digestion and absorption by disrupting gastrointestinal function, digestive enzymes, gut microbiota, and epithelial integrity. This article reviews the mechanisms underlying MP–nutrient interactions, their implications for fish health and nutrient bioavailability, and the potential of nutritional interventions such as antioxidants, functional feed additives, and probiotics to mitigate these effects. It also highlights recent research trends (2013–2026) and identifies key knowledge gaps, emphasizing the need for realistic long-term exposure studies and standardized MP characterization to support effective nutritional management in aquaculture.

## 1. Introduction

Global aquaculture now provides more than half of the fish consumed worldwide, but its sustainability is increasingly challenged by microplastic (MP) pollution (Law & Narayan, 2022). Unlike many environmental contaminants, MPs primarily affect the gastrointestinal tract, where they interfere with nutrient digestion, absorption, and metabolism. Microplastics have been reported in the gut contents of more than 728 fish species across marine and freshwater environments, highlighting their widespread occurrence (Hossain & Olden, 2022). Once ingested, MPs can obstruct digestive transit, adhere to intestinal tissues, disrupt epithelial integrity, and impair nutrient utilization, ultimately affecting fish growth and health (Wright & Kelly, 2017). In aquaculture, MPs originate from contaminated water, degraded plastic infrastructure, and aquafeed ingredients, including fishmeal, fish oil, plant-based feed materials, feed-processing equipment, and packaging, making dietary exposure a significant pathway even in biosecure production systems (Law & Narayan, 2022; Xie et al., 2026; Huang et al., 2020). This article focuses on the

interactions between MPs and nutrient physiology, reviewing their effects on digestive enzymes, gut microbiota, and nutrient bioavailability, while highlighting nutritional mitigation strategies and identifying research gaps relevant to sustainable aquaculture.

## 2. Physicochemical Characteristics Governing Gut Interactions

The biological consequences of MP ingestion are strongly modulated by polymer identity, particle size and morphology rather than being a uniform function of "microplastic" as a single category. Fiber-shaped particles have been shown to cause greater intestinal injury than fragments, which in turn are more damaging than spherical microbeads, likely reflecting differences in how each morphology abrades or lodges within the mucosal lining. Smaller particles, including the nanoplastic size fraction below 100nm, are more capable of crossing the intestinal epithelium and translocating to internal organs, whereas larger microplastics tend to remain within the gut lumen and are more directly implicated in mechanical obstruction (Huang et al 2020).



Polymer type also governs enzymatic interaction. In vitro digestion trials using representative fish digestive enzymes have shown that polyamide and polyethylene terephthalate particles undergo measurable surface degradation when exposed to pepsin and lipase under simulated gastric and intestinal conditions, indicating that the fish digestive environment is not merely a passive conduit for MPs but can partially interact with and alter particle surfaces, with implications for both particle fate and enzyme function (Di Bonito et al. 2026).

### 3. Gastrointestinal Fate: Ingestion, Retention and Egestion Dynamics

Following ingestion, MPs traverse the fish gastrointestinal tract with residence times influenced by particle density, gut motility and feeding frequency. Retention within the stomach and anterior intestine can reduce the effective volume available for feed bolus processing, while adherence to mucus layers may prolong local exposure time and increase the likelihood of epithelial contact (Wright & Kelly, 2017). Structural damage to intestinal villi and microvilli has been documented following MP exposure, including flattening and fusion of villous architecture that reduces the absorptive surface area available for nutrient uptake, a change directly analogous to villous atrophy seen in other causes of malabsorption (Subaramaniyam et al. 2023).

In farmed pompano (*Trachinotus blochii*), metabolomic profiling of intestinal contents following MP exposure revealed disruption to amino acid, glucose and lipid metabolism pathways, indicating that the digestive and absorptive consequences of MP exposure extend well beyond visible tissue damage into the biochemical processing of core macronutrients (Yao et al. 2024). Comparable findings in tilapia (*Oreochromis urolepis*) linked structural small intestinal injury to impaired growth performance, reinforcing that gut-level MP effects can propagate into whole-animal production outcomes relevant to farm economics.

### 4. Impacts on Digestive Enzyme Activity and Macronutrient Digestion

Digestive enzyme activity is among the most directly nutrition-relevant endpoints affected by MP exposure, though the direction of effect is not uniformly suppressive. In peled whitefish (*Coregonus peled*) larvae, short-term polystyrene microplastic exposure significantly stimulated alpha-amylase and non-specific esterase activity within 24 hours, while pancreatic trypsin and bile salt-activated lipase activity increased only after six days of continued exposure, alongside elevated intestinal aminopeptidase N activity (Frank et al. 2023). This time-dependent pattern suggests an initial compensatory or stress-induced upregulation of digestive enzymes that may not be sustainable and could reflect early metabolic strain rather than genuine digestive enhancement.

Other studies report the opposite direction of effect under different exposure regimes: reduced digestive enzyme activity accompanying intestinal structural damage and diminished feed conversion in juvenile guppies (*Poecilia reticulata*) (Huang et al. 2020) and shortened lifespan alongside hepatic dysfunction and impaired digestive performance in the short-lived annual fish *Nothobranchius guentheri* following chronic dietary MP intake (Xiao et al. 2023). Reconciling these divergent findings likely requires attention to exposure duration, particle dose, developmental stage and species-specific digestive physiology, all of which vary considerably across the existing literature and complicate direct cross-study comparison.

### 5. Microplastic-Induced Gut Microbiota Dysbiosis and Nutrient Cycling

The fish gut microbiota performs essential digestive and metabolic functions, including fermentation of otherwise indigestible substrates, synthesis of short-chain fatty acids and modulation of host immune and endocrine signalling, all of which directly influence



nutrient assimilation efficiency (Kanika et al. 2025; Rai et al. 2025). Microplastic exposure has repeatedly been shown to alter the composition and abundance of this microbial community, producing a dysbiotic state characterized by reduced diversity, compromised gut barrier integrity and increased oxidative stress within the intestinal environment (Cao et al. 2024).

In juvenile guppies, MP exposure impaired digestive performance, stimulated an inflammatory immune response and induced measurable gut microbiota dysbiosis simultaneously, illustrating how these three consequences of MP ingestion are mechanistically intertwined rather than independent outcomes (Huang et al. 2020). Because core bacterial phyla such as Firmicutes, Proteobacteria and Bacteroidetes contribute differentially to nutrient processing and short-chain fatty acid production, shifts in their relative abundance following MP-induced dysbiosis can directly alter the nutrient pool available for host absorption, independent of any direct damage to host digestive enzymes (Oz et al. 2026).

## 6. Trophic Transfer and Bioaccumulation Along Aquaculture Food Webs

Microplastics can be transferred through aquatic food webs when lower trophic organisms ingest them and are subsequently consumed by fish, making trophic transfer an important exposure route in aquaculture

(Jo et al., 2025). Farmed fish may also acquire MPs through fishmeal and fish oil produced from contaminated forage fish, even without direct environmental exposure (Xie et al., 2026). The extent of bioaccumulation and toxicity depends on factors such as particle size, dose, exposure duration, feeding rate, and species-specific physiology (Jo et al., 2025; Ghosh, 2025). MP bioaccumulation can also alter haematological and biochemical parameters, indicating systemic effects that may impair nutrient transport and metabolic function (Jo et al., 2025; Ghosh, 2025).

## 7. Species- and Life-Stage-Specific Vulnerabilities

Susceptibility to MP-mediated nutrient disruption varies considerably across farmed species and developmental stages, reflecting differences in gut morphology, feeding mode, metabolic rate and digestive maturity. Larval and early juvenile stages are generally reported as more vulnerable given their comparatively undeveloped gut epithelium and higher surface-area-to-volume ratio, while some documented enzyme responses in early life stages appear as transient stimulation rather than immediate suppression, complicating risk classification based on enzyme activity alone. Table 1 summarizes representative findings across several commercially relevant species.

| Species                                   | Life Stage | MP Type/Size             | Primary Gut/Nutritional Effect                                                                 |
|-------------------------------------------|------------|--------------------------|------------------------------------------------------------------------------------------------|
| Peled whitefish<br>(Coregonus peled)      | Larvae     | Polystyrene microspheres | Time-dependent stimulation of amylase, esterase, trypsin, lipase and aminopeptidase N activity |
| Guppy (Poecilia reticulata)               | Juvenile   | Polystyrene MPs, dietary | Impaired digestive performance, immune stimulation, microbiota dysbiosis                       |
| Annual fish<br>(Nothobranchius guentheri) | Adult      | Dietary MPs, chronic     | Impaired digestion, hepatic dysfunction, shortened lifespan                                    |



|                                         |          |                                               |                                                                                     |
|-----------------------------------------|----------|-----------------------------------------------|-------------------------------------------------------------------------------------|
| Golden pompano (Trachinotus blochii)    | Juvenile | Polystyrene, 5 µm spherical                   | Disrupted amino acid, glucose and lipid metabolism; altered gut microbiota          |
| Nile tilapia (Oreochromis urolepis)     | Juvenile | Not specified                                 | Small intestinal structural damage; impaired growth                                 |
| European seabass (Dicentrarchus labrax) | Juvenile | Fluorescent microbeads, 1–5 µm, 50 mg/kg feed | Intestinal absorption and hepatic translocation; oxidative stress gene upregulation |
| Rainbow trout (Oncorhynchus mykiss)     | Fry      | Dietary MPs with plastic additives            | Elevated oxidative stress biomarkers                                                |

## 8. Nutritional Mitigation Strategies

Because eliminating environmental MP exposure in the near term is not a realistic prospect for most aquaculture operations, nutritional mitigation has emerged as the most immediately actionable line of defense for preserving fish gut health and nutrient utilization efficiency in MP-impacted systems (Xie et al. 2026; Oz et al. 2026).

### 8.1 Antioxidant Supplementation

Dietary astaxanthin, particularly in microencapsulated form, has shown consistent efficacy in mitigating MP-induced oxidative stress across multiple species. In European seabass juveniles, microencapsulated astaxanthin supplementation counteracted the upregulation of superoxide dismutase and catalase genes triggered by dietary microbead exposure, while the microcapsule matrix itself appeared to promote coagulation of microplastic particles within the gut, potentially limiting their absorption (Zarantoniello et al. 2024). A comparable formulation produced similar

oxidative stress mitigation in rainbow trout fry (Şener et al. 2025).

### 8.2 Functional Additives and Microbiome-Directed Approaches

Broader nutritional detoxification frameworks propose combining macronutrient optimization, such as adjusting dietary protein and energy density to support metabolic resilience, with micronutrient fortification using selenium, zinc and antioxidant vitamins and functional additives including probiotics and microalgae-derived compounds, to simultaneously support antioxidant defense, phase I and phase II detoxification pathways and cellular repair mechanisms in fish exposed to complex xenobiotic mixtures that include microplastics (Oz et al. 2026). Probiotic and prebiotic interventions in particular have been proposed as a means of stabilizing gut microbiota composition against MP-induced dysbiosis, thereby indirectly preserving the microbial contribution to nutrient cycling described in Section (Kanika et al. 2025; Rai et al. 2025).

| Mitigation Strategy           | Mechanism                                                | Reported Effect                                           |
|-------------------------------|----------------------------------------------------------|-----------------------------------------------------------|
| Microencapsulated astaxanthin | Antioxidant gene modulation; particle coagulation in gut | Reduced sod1/sod2/cat upregulation; limited MP absorption |





|                                                |                                   |                                                        |
|------------------------------------------------|-----------------------------------|--------------------------------------------------------|
| Macronutrient optimization (protein/energy)    | Metabolic resilience support      | Improved capacity to buffer xenobiotic stress          |
| Micronutrient fortification (Se, Zn, vitamins) | Enhanced antioxidant defense      | Support for endogenous ROS-scavenging systems          |
| Probiotics/synbiotics                          | Microbiota stabilization          | Reduced dysbiosis; preserved nutrient cycling capacity |
| Phytogenic compounds/microalgae additives      | Detoxification pathway activation | Support for phase I/II detoxification enzymes          |

## 9. Bibliometric Analysis of Research Trends (2013–2026)

Bibliometric analyses indicate a rapid increase in research on microplastics (MPs) in aquatic environments over the past decade. Publications indexed in the Web of Science Core Collection increased from just two articles in 2013 to 289 in 2023, demonstrating growing scientific interest in this field (Yang et al., 2025). Similarly, a Scopus-based analysis identified 1,892 publications between 2011 and 2024, with research output accelerating after 2016 and China emerging as the leading contributor, followed by the United States and the United Kingdom (Mai et al., 2025). Keyword co-occurrence analyses identify oxidative stress and intestinal damage as major research hotspots, underscoring the increasing focus on gut health and nutritional impacts of MPs. However, inconsistent particle characterization methods and highly variable exposure protocols continue to limit comparisons across studies and hinder robust meta-analyses (Zuo et al., 2025). A freshwater-focused bibliometric study also reported a 73.13% average annual growth rate in publications during 2013–2023, with *Science of the Total Environment* and *Environmental Pollution* among the leading journals and China, Germany, and the United States as the most productive countries (Yildirim et al., 2024). Despite this rapid growth, research remains concentrated on environmental

occurrence and ecotoxicology, whereas studies addressing digestive enzyme activity, nutrient bioavailability, and nutritional mitigation in aquaculture are comparatively limited (Mai et al., 2025; Yang et al., 2025; Öz & Üstüner, 2026).

## 10. Conclusion

Microplastic contamination has emerged as a significant nutritional stressor in aquaculture, impairing digestion, gut microbiota, intestinal integrity, and nutrient utilization. Current evidence suggests that nutritional strategies such as antioxidant supplementation and microbiome-targeted feed additives can help mitigate these adverse effects. Future research should prioritize realistic long-term exposure studies and standardized microplastic characterization to support the development of effective, species-specific nutritional interventions.

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# Aphena®: Kairomone Technology in Sustainable Pest Management

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The escalating ecological and agronomic limitations associated with indiscriminate insecticide use have accelerated the transition towards sustainable, biodiversity-based pest management strategies. Among these, kairomone-mediated technologies have emerged as a transformative approach that exploits naturally occurring chemical communication to enhance the efficacy of indigenous natural enemies. Aphena®, a controlled-release formulation based on the aphid alarm pheromone (*E*)- $\beta$ -farnesene, exemplifies this paradigm by attracting predators and parasitoids, thereby reinforcing conservation biological control without exerting direct insecticidal effects. By augmenting ecosystem services, preserving beneficial arthropods and pollinators, mitigating insecticide resistance, and reducing pesticide residues, Aphena® aligns seamlessly with the principles of Integrated Pest Management. Its ecological mode of action also offers considerable promise for environmentally sensitive production systems such as mulberry sericulture, where pesticide use is severely constrained by the susceptibility of *Bombyx mori*. Integration of kairomone technology with ecological engineering, microbial biopesticides, and advanced behavioural interventions could establish a residue-free, climate-resilient, and biologically sustainable framework for next-generation pest management in agriculture and sericulture.

## Introduction

The unprecedented intensification of agricultural production over the past several decades has been accompanied by an equally substantial dependence on synthetic insecticides for safeguarding crop productivity. Although chemical pesticides have contributed significantly to increased agricultural output, their indiscriminate and repetitive application has simultaneously endangered a multitude of ecological, environmental, and economic challenges, including the rapid evolution of insecticide resistance, resurgence of secondary pests, contamination of soil and water resources, disruption of ecosystem functioning, and the inadvertent elimination of beneficial arthropods. These concerns have catalysed a paradigm shift from chemically intensive crop protection towards ecologically resilient pest management strategies that exploit

naturally occurring biological interactions. Within this evolving framework, semiochemical-based technologies have emerged as one of the most promising innovations, offering opportunities to manipulate insect behaviour in a manner that is environmentally benign, species-selective, and biologically sustainable. Among the most notable developments is **Aphena®**, a kairomone-based attractant that exemplifies the application of chemical ecology in modern agriculture by enhancing the activity of indigenous natural enemies rather than exerting direct toxic effects on pest populations.

## Leveraging Semiochemical Communication for Sustainable Agriculture

Unlike conventional insecticides, which induce mortality through physiological toxicity, Aphena®



functions by exploiting the sophisticated chemical communication networks that have evolved among plants, herbivorous insects, and their natural enemies over millions of years. The formulation contains **(E)- $\beta$ -farnesene (EBF)**, the principal alarm pheromone released by numerous aphid species when attacked by predators. While this volatile alert neighbouring aphids to impending danger, it simultaneously serves as a highly reliable kairomonal cue for predators and parasitoids, enabling them to locate aphid colonies with remarkable precision. Apthena® harnesses this naturally occurring ecological interaction by releasing controlled quantities of EBF from a **capsule suspension (CS)** formulation, thereby mimicking the chemical signatures associated with aphid-infested crops and attracting a diverse assemblage of beneficial arthropods, including ladybird beetles, hoverflies, lacewings, parasitoid wasps, and other generalist predators. Importantly, the product possesses no direct insecticidal activity against aphids; instead, it strengthens the crop's intrinsic biological defence mechanisms by enhancing conservation biological control, a cornerstone of Integrated Pest Management (IPM).

A distinguishing feature of Apthena® is its controlled-release technology, which permits the gradual emission of kairomonal signals for approximately **20–30 days** following application, thereby extending the period during which beneficial insects are recruited into the crop canopy. According to product recommendations, the attractant is generally applied at **0.3–0.5 L ha<sup>-1</sup>** using **100–300 L of water per hectare** and may be reapplied at intervals of about **14 days**, with no prescribed limit on the number of treatments. Maximum efficacy is achieved when applications are made **preventively**, preferably before substantial aphid colonisation and under conditions favourable for beneficial insect activity, typically at temperatures above **12°C**. Unlike conventional insecticides that are intended to suppress established infestations rapidly, Apthena® is designed to reinforce ecological resilience by

facilitating the early establishment of predator and parasitoid populations before pest densities exceed economic thresholds.

The scientific rationale underpinning Apthena® is firmly rooted in decades of research in chemical ecology demonstrating that **(E)- $\beta$ -farnesene** is among the most effective semiochemicals mediating predator–prey interactions in aphid ecosystems. Behavioural studies have further revealed that natural enemies often respond more strongly to blends of aphid alarm pheromones and herbivore-induced plant volatiles than to individual compounds alone, reflecting the remarkable complexity of insect olfactory perception. Consequently, modern kairomone formulations seek to reproduce these ecologically relevant chemical landscapes, thereby improving the efficiency with which predators and parasitoids locate prey under field conditions. Rather than disrupting ecological processes, such technologies reinforce ecosystem services by enhancing natural pest suppression, conserving biodiversity, protecting pollinators and other non-target organisms, reducing pesticide residues on agricultural commodities, and contributing to long-term insecticide resistance management because their mode of action is behavioural rather than toxicological.

### **Integrating Kairomones into Sustainable Crop Protection**

Another noteworthy attribute of Apthena® is its broad applicability across diverse agricultural production systems, including field crops, vegetables, fruit crops, ornamentals, forestry plantations, and protected cultivation. Because its mode of action is behavioural rather than toxicological, it is inherently compatible with biological control agents, selective insecticides, habitat manipulation, flowering refugia, banker plant systems, microbial biopesticides, and other components of Integrated Pest Management. By enhancing the abundance and foraging efficiency of





naturally occurring predators and parasitoids, kairomone-based attractants contribute to improved ecosystem services, including biological pest suppression, biodiversity conservation, pollinator protection, reduced pesticide residues, and mitigation of insecticide resistance. These attributes make the technology particularly relevant for environmentally sensitive production systems where chemical insecticide use is either undesirable or severely restricted.

### Potential Applications of Kairomone Technology in Mulberry Sericulture

Among such systems, **mulberry sericulture** represents one of the most promising yet underexplored avenues for the application of kairomone technology. Mulberry cultivation is unique because the domesticated silkworm, *Bombyx mori*, is extraordinarily susceptible to even trace quantities of insecticide residues, severely limiting the use of conventional chemical pesticides. Consequently, sap-feeding pests such as aphids, whiteflies, thrips, jassids, pink mealybugs, and spiralling whiteflies continue to inflict substantial economic losses by extracting phloem sap, inducing chlorosis and leaf curling, depositing honeydew that promotes sooty mould development, and ultimately deteriorating mulberry leaf quality, which directly influences silkworm nutrition, larval development, cocoon yield, and raw silk quality. Under these circumstances, kairomone-based attractants offer a compelling ecological alternative by recruiting naturally occurring predators—including coccinellids, chrysopids, syrphids, anthocorids, and parasitoid wasps—into mulberry plantations, thereby strengthening conservation biological control without exposing silkworms to hazardous pesticide residues.

### Conclusion: From Chemical Control to Ecological Intelligence

Although Apthema® has primarily been developed for enhancing the biological control of aphids in conventional agricultural systems, the underlying principles of kairomone-mediated behavioural manipulation possess much broader implications for sustainable sericulture. Future research should focus on identifying kairomonal blends specific to mulberry-associated sucking pests and developing controlled-release formulations capable of sustaining predator activity throughout the cropping season. Such technologies could be effectively integrated with ecological engineering practices, including flowering border plants, insectary strips, banker plants, conservation of natural enemy refuges, microbial biopesticides, habitat diversification, and emerging molecular approaches. The convergence of these complementary technologies has the potential to establish a next-generation, residue-free, biodiversity-friendly, and climate-resilient pest management framework for mulberry cultivation. Beyond reducing pesticide dependence, such an integrated strategy would enhance the stability of natural enemy populations, improve ecosystem functioning, safeguard silkworm health, and ensure the sustained production of high-quality mulberry foliage essential for premium silk production. Thus, while Apthema® itself represents a commercial manifestation of kairomone technology, its broader ecological concept offers an exciting blueprint for future innovation in sericulture, where environmentally compatible and biologically sustainable pest management solutions remain an urgent research priority.

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# Eat Smart, Absorb Smarter: The Science Behind Nutrition

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Food is a dynamic system in which many elements interact with one another in unexpectedly potent ways; it is not merely a collection of discrete nutrients. Vitamins, minerals, lipids, proteins, and plant components all work together during a meal. Rather, they have an impact on each other, sometimes increasing advantages and other times restricting the absorption of nutrients. These connections, referred to as food-food interactions, are crucial to our bodies nutritional processing.

Consider eating a healthy diet, we typically concentrate on individual nutrients, such as protein to build muscle, calcium to strengthen bones, or vitamin C to increase immunity. But nutrients don't function on their own. They work together in a complicated system within the body, supporting, enhancing, or occasionally impeding one another's functions. Understanding these relationships can alter how we view and manage our nutrition.

Comprehending these relationships can significantly impact daily health. The arrangement of foods on your plate can have an impact on how well your body absorbs vital nutrients, how they are metabolised, and ultimately how they support immunity, energy levels, and general health. We may make better food choices by realising these small but significant links, transforming basic meals into more nutritious and health-promoting combinations.

Food has many interactions; they can be 1. Complementary interaction 2. Conflicting interaction 3. Enhancing interaction 4. Inhibitory interaction 5. Synergistic interaction.

## 1.Complementary Interaction:

By offering a better mix of vital nutrients, eating two or more foods together can actually improve a meal's overall nutritional quality. We refer to this kind of food-food exchange as a positive interaction. In some situations, one food can enhance the absorption of specific components or provides nutrients that another may not have. Traditional Indian meals have been improving nutrient intake, supporting improved digestion, and promoting general health in a straightforward, useful way for millennia by carefully blending a variety of nutrient-rich foods.

These are some examples of complementary exchange:

- Dal and Rice or Roti and Dal: High-quality protein can be found in traditional Indian dishes like dal-chawal or roti with dal. Pulses like lentils are high in lysine, yet cereals like rice and wheat are high in methionine. They are particularly beneficial in vegetarian diets since they combine to make a complete protein
- Palak with Lemon: Squeezing lemon juice into palak sabzi or palak dal improves the



absorption of iron. Iron is present in spinach in a form that is difficult to absorb, but vitamin C from lemon helps change it.

- Tomato-based Curries with Ghee or Oil: Cooking foods like paneer butter masala or tomato curry with healthy fats like ghee or oil makes them even more advantageous.
- Vegetable Salads with Peanuts or Seeds: Indian salads (kachumber) topped with roasted peanuts or sesame seeds offer a nutritious and satisfying combination of fibre, healthy fats, protein, and vital minerals like zinc and magnesium.
- Vegetable Salads with Peanuts or Seeds: Indian salads (kachumber) topped with roasted peanuts or sesame seeds offer a nutritious and satisfying combination of fibre, healthy fats, protein, and vital minerals like zinc and magnesium.

## 2.Conflicting Interaction:

Food interactions of this nature may impede the body's ability to absorb, metabolize and use some nutrients or drugs that have been introduced into the body via other foods, and may result in deficiencies or other adverse effects. It is thus useful to understand the interactions between foods and to maintain a varied and balanced diet, so that any impediments to absorption do not obstruct the provision of optimal nutrition and health. For example, milk and citrus fruit may curdle in the stomach, due to the acidity of the latter, occasionally causing an upset stomach.

These are some examples of conflicting interaction:

- Calcium and Iron: Dietary calcium (milk and milk products) taken together with dietary iron (green leafy vegetables, nuts, legumes, and pulses) may be antagonistic. Calcium competes with iron for the same absorption sites. This is

more important with iron deficiency. Hence, it is advisable to space these nutrients several hours apart.

- Coffee and Calcium: Calcium absorption may decrease when calcium-rich foods are consumed with coffee. Caffeine in coffee may also increase the amount of calcium lost in urine. Limit coffee consumption with or right after meals high in calcium to optimize absorption in the gut.
- Copper and Zinc: Excess zinc intake may interfere with copper absorption and vice versa. Hence excessive intake of either one can induce deficiency of the other. A variety of food sources for both minerals should be maintained in order to avoid these imbalances.
- Alcohol and Nutrient Absorption: Drinking alcohol can have a detrimental effect on the metabolism and absorption of a number of vital nutrients, such as vitamin B12, thiamine, and folate. Long-term consumption can lead to deficits and related health issues, and it may also increase the excretion of these minerals.

## 3. Enhancing Interaction:

A type of food-food interaction known as "enhancing interactions" occurs when two or more foods are combined to boost the bioavailability, absorption, or efficacy of particular nutrients or bioactive chemicals. These interactions can enhance foods' nutritional value and lead to better health consequences. Optimising nutrition utilisation and overall physiological performance can therefore be greatly aided by incorporating a wide variety of nutrient-rich foods and mixing them effectively.

These are some examples of Enhancing interaction:

- Vitamin D and Calcium: Eating meals high in both vitamin D and calcium improves the body's absorption of calcium. By promoting intestinal calcium absorption, vitamin D supports bone



mineralisation and lowers the risk of diseases like osteoporosis.

- **Iron with Vitamin C:** Eating meals high in vitamin C greatly enhances the absorption of non-heme iron, which is typically present in plant-based diets. Iron's bioavailability is increased when vitamin C helps transform it into a more soluble and absorbable state. Because of this, it is advised to combine meals high in iron, such as legumes or leafy greens, with sources of vitamin C.
- **Turmeric with Black Pepper:** Consuming black pepper increases the bioavailability of curcumin, the main active ingredient in turmeric. The main ingredient in black pepper, piperine, enhances the absorption of curcumin and amplifies its antioxidant and anti-inflammatory effects.
- **Tomatoes with Olive Oil:** When ingested with dietary lipids like olive oil, lycopene, a pigment found in tomatoes, shows increased absorption. The presence of lipids improves the solubility and bioavailability of lycopene, thereby enhancing its antioxidant effects.
- **Green Tea with Lemon:** Adding lemon to green tea can improve its absorption of catechins, which are bioactive substances with antioxidant qualities. Lemon's vitamin C enhances the body's absorption of catechins and stabilises them.

#### 4. Inhibitory Interaction:

When some foods or their constituents decrease the absorption, metabolism, or biological efficacy of particular nutrients or bioactive chemicals, this is referred to as an inhibitory food–food interaction. These interactions can have a detrimental effect on a meal's nutritional value and restrict the body's capacity to get the most out of the nutrients it consumes. Improving eating habits and avoiding

possible vitamin deficits require an understanding of these connections.

These are some examples of inhibitory interaction:

- **Antinutrients:** Phytates, oxalates, and tannins are examples of naturally occurring substances found in food that can bind to vital minerals and decrease their absorption. For instance, the bioavailability of minerals like iron, calcium, and zinc may be restricted by phytates found in legumes, nuts, and seeds. On the other hand, conventional food processing methods like heating, sprouting, and soaking can greatly lower antinutrient levels and improve mineral absorption
- **Protein Inhibitors:** Certain meals have compounds that prevent the digestion of proteins. For example, soybeans and other legumes include trypsin inhibitors that can prevent the digestion and absorption of proteins. Appropriate processing techniques like fermentation and heating can reduce these inhibitory effects.
- **Fibre Interactions:** Consuming a lot of dietary fibre, especially from whole grains, might hinder the absorption of minerals like zinc and iron. However, fibre also has positive effects, such as improving satiety and decreasing the digestion of carbohydrates, which highlights the necessity for balanced ingestion.
- **Competitive Absorption:** In the gastrointestinal tract, certain nutrients have similar absorption pathways. They may compete with one another for absorption when taken in large quantities, which could result in decreased uptake of one or more nutrients.

#### 5. Synergistic Interaction:

When certain meals or their components are consumed together, the health benefits are increased or magnified compared to when they are consumed





separately. This is known as a synergistic food-food interaction. The total impact of these interactions is greater than the sum of each food's individual contributions. Promoting general health, increasing nutrient utilisation, and improving dietary quality can all be greatly aided by comprehending and making use of these synergistic interactions. Better taste qualities, enhanced antioxidant activity, enhanced protein quality, and efficient glycaemic control could all result from these interactions.

These are some examples of synergistic interaction:

- **Nutrient Enhancement:** The bioavailability and absorption of nutrients can be greatly increased by specific dietary combinations. For instance, consuming meals high in vitamin C in addition to plant-based iron sources improves the absorption of non-haem iron by changing it into a form that is more accessible. In a similar vein, dietary fats help absorb fat-soluble vitamins like A, D, E, and K.
  - **Antioxidant Synergy:** Foods high in various antioxidants can complement one another to offer better defence against oxidative stress. For example, mixing meals high in vitamin C, like fruits, with foods high in vitamin E, like nuts and seeds, might increase the total antioxidant capacity since these vitamins support and replenish one another's action.
  - **Phytochemical Interactions:** Bioactive substances like polyphenols and carotenoids, which provide a number of health advantages, are present in many plant-based foods. These substances may work in concert to increase their biological effects when taken together. For instance, the absorption of carotenoids such as lycopene from tomatoes can be enhanced by the presence of dietary fat.
  - **Protein Complementation:** A full amino acid profile can be obtained by combining several plant-based protein sources. For example, by providing limiting amino acids, cereals and legumes enhance total protein quality and guarantee sufficient consumption of essential amino acids.
  - **Glycaemic Control:** Blood glucose levels can be regulated by combining foods with different glycaemic indices. When protein, fibre, or healthy fats are consumed with carbohydrates, digestion and absorption can be slowed, resulting in a more progressive release of glucose and longer satiety.
- .....



# Marine Algal Bioprospecting: Sustainable Innovations Driven by Marine Algae

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Marine algal bioprospecting represents a transformative approach for sustainable resource utilisation amid escalating ecological crises. This review synthesises recent advances in harnessing algae—both micro and macro—for multifaceted environmental and industrial applications. Algae's rapid growth, carbon sequestration efficiency (>50% global carbon fixation), and ability to thrive in non-arable land/wastewater position them as ideal bioresources. Key innovations include: (1) Sustainable aquafeeds reducing fisheries dependency (e.g., omega-3-rich algal oils replacing fish oil); (2) Bioplastics (PHA/PHB) from algal polymers degrading 90% faster than petroleum plastics; (3) Phycoremediation using *Chlorella* and cyanobacteria to detoxify wastewater and absorb heavy metals; and (4) Carbon-neutral biofuels with higher yield/ha than terrestrial crops. We further highlight high-value compounds (carrageenan film coatings extending food shelf-life; fucoidan's antiviral potency). Despite challenges in scalable cultivation and economic viability, integrating circular economy models—such as combining wastewater treatment with biomass production—shows promise. Recent CRISPR-enhanced strain development and government initiatives signal growing viability. This work underscores algal bioprospecting as a critical pillar of the blue economy, advocating for policy support and interdisciplinary research to unlock its full potential in achieving SDGs 2, 7, 12, and 14.

## Introduction

Marine bioprospecting, also known as biodiversity prospecting, is the systematic exploration of marine organisms to discover valuable natural compounds, genes, and biomaterials that can be developed into products for pharmaceutical, cosmetic, agricultural, food, and industrial applications without harming marine ecosystems (Morgado & Vieira, 2021). Among marine organisms, algae have emerged as one of the most promising resources due to their remarkable biochemical diversity and wide range of sustainable applications.

The world's oceans cover more than 70% of the Earth's surface and are estimated to contain nearly 91% of undiscovered species, making them an immense reservoir of biological and chemical diversity (National Ocean Service, 2023). Marine algae, ranging from microscopic microalgae to giant

seaweeds, have evolved unique metabolic pathways that enable them to produce valuable bioactive compounds, including omega-3 fatty acids, antioxidants, polysaccharides, pigments, and antimicrobial substances with enormous industrial potential (Blunt et al., 2023).

As the global population grows, the demand for food, renewable energy, environmentally friendly materials, and sustainable aquaculture continues to increase. At the same time, overexploitation of natural resources, climate change, and marine pollution threaten the health of our oceans and food systems (FAO, 2022; IPCC, 2023). Marine algal bioprospecting offers an innovative and environmentally responsible solution by identifying algae that can be used to produce high-value products while reducing pressure on terrestrial resources and wild fisheries (Morgado & Vieira, 2021).



Marine algae require no arable land, consume little or no freshwater, grow rapidly, efficiently capture atmospheric carbon dioxide, and can even be cultivated using wastewater. These unique characteristics make them ideal candidates for supporting a sustainable blue economy through applications in aquaculture, pharmaceuticals, nutraceuticals, biodegradable plastics, biofuels, cosmetics, and environmental remediation (Leal et al., 2013; Wells et al., 2017).

One of the most promising applications of marine algal bioprospecting is in sustainable aquaculture. As aquaculture expands to meet the world's growing seafood demand, reliance on fishmeal and fish oil derived from wild fisheries has become a major environmental concern. Marine algae provide sustainable alternatives rich in proteins, essential fatty acids, vitamins, minerals, and natural pigments that can improve aquafeed quality while reducing dependence on finite marine resources (Chakraborty, 2023; Shah et al., 2018). Through such innovations, marine algal bioprospecting is paving the way for a greener, more resilient, and sustainable future.

### **Marine Algae: An “Untapped Resource” of Natural Products?**

The vast and largely unexplored taxonomic, genetic, and chemical diversity and complexity of marine organisms including algae is considered an “untapped source” of valuable products and is currently investigated at many levels. Recent research has focused on a range of novel uses of algae in a wide range of industrial sectors, from agricultural, health care and cosmetics, to pharmaceutical uses, supported by advances in the chemical characterization and analytical techniques of new compounds and the ability to screen for different bioactivities in high-throughput systems (Stengel and Connan, 2015).

Marine microalgae are a group of diverse photosynthetic organisms rich in bioactive components such as polysaccharides, lipids, proteins, pigments, vitamins, and minerals. They produce a number of valuable compounds that have significant roles in the pharmaceutical, biomedical, nutraceutical, and food industries (Jain et al., 2022).

The algae can be collected from various environments, including freshwater and marine habitats (Sawarkar et al., 2019). The collected algae are then processed using various technologies to develop genetic material that exhibits desirable characteristics (Santhakumaran et al., 2019). The algae are screened for bioactivity profiling of phytotherapeutic molecules and drugs. This involves testing the algae for various biological activities, such as antimicrobial, antioxidant, or anti-inflammatory activities (Mani et al., 2017). The desirable characteristics identified in the algae are then used to develop commercial products (Santhakumaran et al., 2019). These can include biofuels, nutraceuticals, pharmaceuticals, and other bioproducts. Metabolomics can be used to identify specific metabolites that lead to the production of biofuels and high-value bio renewables by the valorisation of carbon dioxide (CO<sub>2</sub>) in these algal cell factories (Hughes et al., 2021).

### **Algal based marine natural products**

#### **Microalgae: Sustainable Solutions from Microscopic Organisms**

Marine microalgae account for about 50% of global organic carbon fixation. They can be used as food (e.g., Spirulina), feed and fertilizer. Latest tendencies in microalgal biotechnology includes production of bioactive compounds and their use in pharmaceutical, nutraceutical and cosmetic industries. Biofuels from microalgae is globally accepted as new generation biofuels. Microalgal phyco-remediation is the best technology of



bioremediation in CO<sub>2</sub> sequestration and waste water treatments (Preetha and Vijayan, 2010).

**Table.1 Major Applications of Marine Microalgae in Sustainable Development**

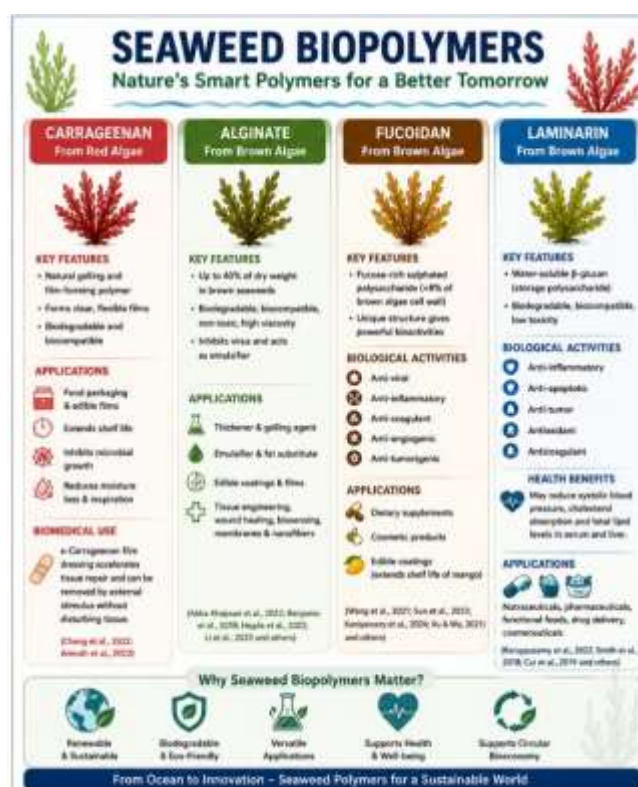
| Application                          | Marine Algal Product/Technology                                                    | Major Applications                                                                                               | Benefits                                                                                                           | References                                                                                                       |
|--------------------------------------|------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------|
| <b>Biopolymers &amp; Bioplastics</b> | Polyhydroxyalkanoates (PHA), Polyhydroxybutyrate (PHB), polyesters, polyamides     | Biodegradable plastics, antibacterial coatings, antifouling paints, fishing beads, eco-friendly products         | Reduces plastic pollution; renewable alternative to petroleum plastics; biodegradable and environmentally friendly | Abdel-Latif et al. (2022); Kavitha et al. (2018)                                                                 |
| <b>Space Research</b>                | <i>Chlorella vulgaris</i> , <i>Euglena</i> in photobioreactors                     | Oxygen generation, carbon dioxide removal, edible biomass production, wastewater recycling, life-support systems | Supports long-duration space missions; produces oxygen and protein-rich food while recycling waste                 | Verrecchia et al. (2015); Trent et al. (2010)                                                                    |
| <b>Biofuel Production</b>            | Lipid-rich microalgae                                                              | Biodiesel, renewable transportation fuel, fishing vessel fuel                                                    | Carbon-neutral energy, high biomass productivity, low land requirement, wastewater utilization                     | Tuan (2013); Brandon (2019); Rafa et al. (2021)                                                                  |
| <b>Biogas Production</b>             | Anaerobic digestion of algal biomass                                               | Methane-rich biogas, hydrogen-methane co-production, renewable electricity generation                            | Renewable energy production, waste biomass utilization, reduced greenhouse gas emissions                           | Davis et al. (2011); Singh & Gu (2010); Srirangan et al. (2012); Jonker & Faaij (2013); Wiecezorek et al. (2014) |
| <b>Phycoremediation</b>              | <i>Chlorella</i> , <i>Scenedesmus</i> , <i>Ankistrodesmus</i> and other microalgae | Wastewater treatment, nutrient removal, carbon dioxide sequestration, heavy metal removal                        | Improves water quality, reduces eutrophication, captures CO <sub>2</sub> , generates valuable biomass              | Mulbry et al. (2008); Olguín (2003); Moreno-Garrido (2008); Rawat et al. (2011); Abeliovich                      |



|                  |                                                                                   |                                                                         |                                                                                                       |                                                                                                                    |
|------------------|-----------------------------------------------------------------------------------|-------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------|
|                  |                                                                                   |                                                                         |                                                                                                       | (2017); Pinto et al. (2002)                                                                                        |
| <b>Aquafeeds</b> | Microalgal proteins, lipids, omega-3 fatty acids, pigments, vitamins and minerals | Fishmeal and fish oil replacement, feed supplements for fish and shrimp | Improves growth, immunity, disease resistance, flesh quality and reduces dependence on wild fisheries | Shah et al. (2018); Becker (2004); Becker (2007); Sarker et al. (2016); Skrede et al. (2011); Hannon et al. (2010) |

## Macroalgae: Sustainable Applications of Seaweeds

Seaweeds, also known as marine algae, are a significant focus in marine bioprospecting due to their diverse bioactive compounds and potential health benefits. Seaweeds possess structurally diverse compounds with various bioactivities, including antihypertensive, anti-inflammatory, and anticarcinogenic activities (Chakraborty, 2022). Due to their polyphenol and carotenoid levels, seaweeds are now being explored as an excellent source of antioxidants (Ghosh et al., 2022). Seaweed processing for the extraction of phytochemicals such as alginate, agar, and carrageenan have wide applications in various ways in day-to-day life (Rao et al., 2018). They are also used as gelation and thickening agents in different food, pharmaceutical, and biotechnological applications (Rhein-Knudsen et al., 2015).



## Bioplastics from seaweed

The global biodegradable plastic market accounts for less than 1% of the overall plastic market, it is expected to grow at a fast pace over the next upcoming years (Aggarwal et al., 2020). Biodegradable plastics have found their end-use in a variety of commercial applications like Bags and toys packing in commercial sector; agricultural foils, horticulture and nursery products in agriculture industry; facemask and washing powder packing





materials in cosmetic industry and toiletry industry; drinking cups, overwrap, straws containers and edible films in food packing industry; capsule coating in pharmaceutical industry (Ashter, 2016). Bioplastic synthesised from seaweed/ starch/ cellulose and other composites has quite good thermal stability, water solubility to some extent, but has a good degradation rate. Since plastic pollution is increasing day by day we can enumerate the use of plastic by this Seaweed based plastic as it is renewable and Eco-friendly in nature (Shravya et al., 2021).

### Conclusion

Algal bioprospecting represents a valuable tool in the sustainable management of fisheries resources, offering multifaceted benefits ranging from improved aquaculture productivity to environmental remediation. By optimizing the nutritional composition of aquaculture feeds through algal bioprospecting, the aquaculture industry can become more sustainable and environmentally friendly, mitigating pressure on wild fish populations and promoting the conservation of marine ecosystems. Continued research and innovation in this field will be essential to unlock the full potential of algae-based solutions and ensure the long-term health and resilience of global fisheries. The advanced research on modern bioengineering techniques and well-established genetic tools like CRISPR–Cas9 (Clustered regularly interspaced palindromic repeats or CRISPR-associated protein 9) should be encouraged to develop recombinant microalgae strains with elevated levels of PHA/PHB inside the cell. With the constant improvements in technology and government support, however, bio-oil has the potential to emerge as a viable alternative to conventional fossil fuels.

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# AI-Powered Digital Marketing: How Artificial Intelligence Is Redefining Brand Growth in 2026

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The digital marketing landscape is undergoing a major transformation as artificial intelligence (AI) becomes a central force in customer engagement, content creation, advertising, and strategic decision-making. In 2026, brands are moving beyond traditional keyword-based marketing toward AI-driven discovery, personalization, and conversational experiences.

One of the most significant changes is the rise of AI-powered search and Generative Engine Optimization (GEO). Consumers are increasingly using AI assistants and conversational search tools to discover information, products, and services. As a result, brands must create authoritative, useful, and context-rich content that can be recognized by AI-driven platforms rather than focusing only on conventional search engine rankings.

AI is also transforming advertising by enabling advanced audience analysis, automated campaign optimization, and personalized customer journeys. Businesses are using AI tools to understand consumer behavior, predict preferences, and deliver relevant messages at the right moment. This shift allows marketers to improve efficiency while creating more meaningful customer experiences.

Another emerging trend is the growth of conversational commerce, where customers discover products through social media, chat platforms, and

AI-powered recommendations. Video-first content, creator partnerships, and interactive experiences are becoming increasingly important as consumers seek authentic and engaging brand interactions.

However, the future of digital marketing will not depend on technology alone. Brands must balance automation with creativity, transparency, and human connection. Customers increasingly value trustworthy content, ethical data practices, and authentic storytelling.

The next generation of digital marketing will belong to organizations that successfully combine artificial intelligence with human creativity. AI may provide speed and intelligence, but strategic thinking, emotional understanding, and genuine customer relationships will continue to define successful brands.

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# Soil Salinity and Its Reclamation: Methods, Impacts, and Management

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Soil salinity is a major form of land degradation that threatens agricultural productivity, soil health, and global food security, particularly in arid and semi-arid regions. The excessive accumulation of soluble salts in the root zone increases the osmotic potential of the soil solution, disrupts ionic balance, impairs nutrient uptake, and deteriorates soil physical, chemical, and biological properties, ultimately leading to reduced crop growth and yield. In India, soil salinization has become an increasing concern owing to improper irrigation practices, inadequate drainage, rising groundwater tables, and the use of poor-quality irrigation water. Effective reclamation of salt-affected soils is therefore essential for restoring soil fertility and ensuring sustainable agricultural production. The impacts of soil salinity and discusses the major reclamation approaches, including physical, chemical, and biological methods. Physical interventions such as drainage improvement, land leveling, and leaching facilitate salt removal, whereas chemical amendments, particularly gypsum, improve soil structure by replacing exchangeable sodium with calcium. Recent advances in biological reclamation, including phytoremediation using halophytes and salt-tolerant plant species, microbial remediation employing halotolerant plant growth-promoting microorganisms, and the application of organic amendments, offer environmentally sustainable alternatives for improving soil quality and enhancing crop tolerance to salinity. The integrated soil management strategies that combine engineering, chemical, biological, and agronomic practices to achieve long-term reclamation of saline soils, improve resource-use efficiency, and enhance the resilience and productivity of salt-affected agroecosystems under changing climatic conditions.

Soil salinity is one of the most serious forms of land degradation, adversely affecting agricultural productivity, soil health, and environmental sustainability. More than 418 million hectares (Mha) of land in over 100 countries are affected by salinity worldwide. Asia accounts for approximately 46% of the world's salt-affected soils, with about 6.27% of its land area affected. In India, nearly 10.0 Mha of land is salt affected, including 5.5 Mha of saline soils and 3.8 Mha of sodic soils, posing a major constraint to sustainable agriculture (ICAR, 2019; Chhabra, 2021; Minhas and Qadir, 2024). Saline soils are characterized by the accumulation of excessive soluble salts, mainly chlorides, sulfates, and bicarbonates of sodium, calcium, and magnesium, in the root zone. High salt concentrations increase the osmotic potential of the soil solution, reducing water availability to plants and causing physiological

drought. As a result, seed germination, nutrient uptake, plant growth, and crop yield are significantly reduced (Rattan Lal, 2020; Xu et al., 2023). In many cases, salinity is associated with sodicity, where excessive exchangeable sodium deteriorates soil structure, reduces infiltration and permeability, and restricts root growth (Oster, 1982; Tóth, 2022). Soil salinization occurs through both natural and human-induced processes. Natural salinity develops due to weathering of salt-bearing parent materials, seawater intrusion, and capillary rise of saline groundwater, whereas secondary salinity results from improper irrigation practices, inadequate drainage, rising groundwater tables, and the use of saline irrigation water (Qadir et al., 2008; Minhas & Qadir, 2024).

According to the United Nations Environment Programme (2021), soil salinization is



a major threat to sustainable agriculture and global food security. The assessment and classification of salt-affected soils are primarily based on electrical conductivity (EC), exchangeable sodium percentage (ESP), and sodium adsorption ratio (SAR), which are widely used to evaluate the severity of salinity and sodicity (Shahid et al., 2013). Reclamation and sustainable management of saline soils require an integrated, site-specific approach that combines chemical, physical, biological, and agronomic interventions. Chemical amendments such as gypsum remain the most effective means of reclaiming sodic soils by replacing exchangeable sodium with calcium, thereby improving soil aggregation, permeability, and root-zone conditions (Oster, 1982). Physical measures, including efficient drainage systems, land leveling, and leaching with good-quality irrigation water, facilitate the removal of excess soluble salts below the root zone and prevent their re-accumulation (Chhabra, 2021; Minhas & Qadir, 2024). In recent years, sustainable biological approaches such as phytoremediation, microbial remediation, and the application of organic amendments including compost, farmyard manure, green manure, and biochar have gained considerable attention because of their ability to improve soil microbial activity, enhance nutrient cycling, increase organic carbon, and restore soil fertility (Arora et al., 2017; Elmeknassi et al., 2024). Furthermore, the cultivation of salt-tolerant crop varieties, precision irrigation, and integrated nutrient management practices can significantly improve crop performance and long-term productivity under saline conditions (Tóth, 2022).

### Natural Causes of Soil Salinity

- **Low rainfall and high evapotranspiration** in arid and semi-arid regions restrict the leaching of soluble salts, leading to their accumulation in the soil profile (Indian Council of Agricultural Research, 2019; Rattan Lal, 2020).

- **Weathering of parent materials** releases soluble salts such as chlorides and sulfates, which gradually accumulate in the soil over time (Shahid et al., 2013).
- **Seawater intrusion in coastal areas** increases soil salinity by introducing dissolved salts into the soil system (Chhabra, 2021).

### Human-Induced Causes of Soil Salinity

- Improper irrigation practices, especially the use of saline or poor-quality water, add significant amounts of dissolved salts to agricultural soils (Minhas & Qadir, 2024).
- Poor drainage and waterlogging raise the groundwater table, causing capillary rise and accumulation of salts in the root zone (Qadir et al., 2008).
- Excessive irrigation and inefficient water management further intensify salt accumulation (United Nations Environment Programme, 2021).
- Continuous use of chemical fertilizers and amendments contributes to long-term salt buildup in soils (Arora et al., 2017).

### Impacts of Soil Salinity

#### 1. Impact on Plant Growth

High concentrations of soluble salts increase the osmotic potential of the soil solution, making water uptake difficult for plants and causing physiological drought. This results in poor germination, stunted growth, and significant yield losses, particularly in salt-sensitive crops (Rattan Lal, 2020; Xu et al., 2023).

#### 2. Impact on Soil Physical Properties

Excess sodium in saline soils causes soil particle dispersion, reduced aggregation, low permeability, and poor aeration. These changes restrict root growth, water movement, and nutrient transport,



leading to nutrient imbalances and ion toxicity (Tóth, 2022; Oster, 1982; Shahid *et al.*, 2013).

### 3. Impact on Soil Biological Properties

Saline soils exhibit reduced microbial activity and biodiversity, which negatively affects organic matter decomposition, nutrient cycling, and overall soil fertility. Over time, this leads to declining soil productivity (Arora *et al.*, 2017; Elmeknassi *et al.*, 2024).

### 4. Impact on Land and Agriculture

At a broader scale, soil salinization contributes to land degradation and desertification, reducing the productive capacity of agricultural land. In irrigated regions, prolonged salinity can render fertile soils unsuitable for cultivation, posing a serious threat to sustainable agriculture and food security (United Nations Environment Programme, 2021; Chhabra, 2021; Minhas & Qadir, 2024; Qadir *et al.*, 2008; Indian Council of Agricultural Research, 2019).

### Reclamation of Saline Soils

Soil salinity reduces crop productivity and soil health, making reclamation essential for sustainable agriculture. Reclamation strategies aim to remove excess salts, improve soil structure, and restore fertility. According to Chhabra (2021) and Shahid *et al.* (2013), effective reclamation combines **chemical, physical, and biological methods**, often applied together depending on soil type, salt levels, and local conditions.



### 1. Chemical Methods

- **Application of gypsum (calcium sulfate):** Replaces sodium ions on soil cation exchange sites, improving soil structure and permeability (Oster, 1982; Tóth, 2022).
- **Use of other chemical amendments:** Calcium chloride, sulfuric acid, or acid-forming fertilizers can also neutralize sodicity and promote leaching of salts (Shankar & Evelin, 2019; Minhas & Qadir, 2024).
- **Leaching with good-quality water:** Following amendment application, irrigation with sufficient water flushes salts below the root zone (Qadir *et al.*, 2008; Xu *et al.*, 2023).

### 2. Physical Methods of Saline Soil Reclamation

Physical methods are designed to remove excess soluble salts from the soil profile, improve water movement, and prevent the re-accumulation of salts in the root zone. These methods are generally used in combination with chemical amendments and proper irrigation management to enhance the efficiency of reclamation.

#### 1. Improving Drainage

Efficient drainage is a prerequisite for successful reclamation of saline soils. Surface and subsurface drainage systems remove excess irrigation and rainwater, lower the groundwater table, prevent waterlogging, and facilitate the leaching of soluble salts beyond the root zone. Adequate drainage also minimizes capillary rise of saline groundwater, thereby reducing secondary salinization (Shahid *et al.*, 2018; Chhabra, 2021).

#### 2. Land Leveling and Contouring

Proper land leveling ensures uniform distribution of irrigation water across the field, preventing localized salt accumulation caused by uneven water application. In sloping areas, contouring reduces





runoff, enhances infiltration, and promotes uniform leaching of salts, thereby improving reclamation efficiency (Shankar and Evelin, 2019).

### 3. Leaching through Irrigation Management

Leaching is the most effective physical method for reclaiming saline soils. It involves applying good-quality irrigation water in excess of crop evapotranspiration requirements to dissolve and transport soluble salts below the crop root zone. Proper irrigation scheduling ensures continuous downward movement of salts while minimizing water wastage. However, successful leaching requires an efficient drainage system to remove the saline drainage water from the field (Qadir et al., 2008; Minhas & Qadir, 2024).

### 4. Scraping

Scraping involves the mechanical removal of salt crusts accumulated on the soil surface. This method is economical and suitable for small areas such as gardens, nurseries, or localized saline patches where surface salt deposition is severe. Since salts continue to migrate upward through capillary action, scraping provides only temporary relief and is generally used as a supplementary reclamation practice.

### 5. Flushing

Flushing refers to washing away surface salt deposits using flowing water before they infiltrate into the soil. This method is particularly useful for soils with surface salt crusts and low infiltration rates. Flushing effectively removes salts from the soil surface but does not reclaim salts present deeper within the soil profile; therefore, it is often followed by leaching and drainage.

### 6. Leaching

Leaching is the principal method for removing excess soluble salts from saline soils. Good-quality irrigation water or rainfall dissolves soluble salts and carries them below the effective root zone. The

effectiveness of leaching depends on soil texture, hydraulic conductivity, water quality, drainage efficiency, and the depth of the groundwater table. Without adequate drainage, leached salts may accumulate again due to capillary rise, reducing the long-term effectiveness of reclamation (Qadir et al., 2008; Shahid et al., 2013).

### 7. Leaching Requirement (LR)

The **Leaching Requirement (LR)** is defined as the minimum fraction of irrigation water that must pass through the root zone to maintain soil salinity below the threshold level tolerated by a particular crop. It is based on the principle of **salt balance**, where the quantity of salts entering the soil through irrigation water is balanced by the quantity of salts removed in the drainage water. Proper estimation of LR is essential for sustainable irrigation management in salt-affected areas, ensuring favorable root-zone salinity while preventing excessive water use (Ayers & Westcot, 1985; Minhas & Qadir, 2024).

Leaching Requirement (LR) =  $\frac{EC_{iw}}{EC_{dw}} \times 100$  Where, EC = Electrical Conductivity in dSm-1; iw = EC of Irrigation water in dSm-1; dw = EC of Drainage water in dSm-1; Ddw = Depth of drainage water in inches; Diw = Depth of irrigation water in inch





### 3. Agronomic and Cultural Methods of Saline Soil Reclamation

In areas where only saline irrigation water is available or when shallow saline water table prevails and soil permeability is low, the following cultural practices are adopted.

**Selection of Crops and Crop Rotations** On the basis of crop tolerance to quality of irrigation water or soil salinity the crops can be classified in four groups viz., Highly tolerant crops: Barley, Sugar beet, datepalm. Tolerant: Tapioca, mustard, coconut, spinach, amaranthus, pomegranate, guava, ber. Semi-tolerant: Ashguard, bitterguard, brinjal, cabbage, cluster bean, Pea, lady's finger, muskmelon, onion, potato, dolichos, sweet potato, tomato, turnip, water melon. Sensitive: Radish, carrot, Coriander, Cumin, Mint, Grape, sweet orange.

**Method of Raising Plants** Crop should be raised by transplanting seedlings (especially vegetables, flowers, fruit trees) than germinating the seeds. • Wild root stocks grafted with a good quality but salinity sensitive scion (Mango, citrus, Guava and ornamental plants like rose).

**Irrigation Practices** Method of water application- follow furrow or drip irrigation, sub surface irrigation systems and sprinkler irrigation. Frequency of irrigation- irrigation more often (frequent) can maintain better water availability & decrease the salinity should not too much irrigations.

**Use of mulching materials** to prevent evaporation losses like straws, plastic sheets etc.

#### Organic Amendments

Organic amendments such as farmyard manure, molasses, sugar factory press-mud, green manures, crop residues, and weeds are commonly incorporated into saline soils to improve soil quality and support the reclamation process over time.

Among these, **green manuring** is particularly effective. Common green manure crops include **Sesbania aculeata (dhaicha or Jantar), sunnhemp, berseem, sengi, and cowpea**. When these crops decompose, they release readily available nutrients, help dissolve calcium compounds, and reduce the high pH of saline and alkali soils. This results in improved soil permeability, enhanced microbial activity, and gradual restoration of soil fertility. **Sesbania aculeata** has been found to be the most effective green manure crop for saline soils.

#### Afforestation

Saline and salt-affected soils can be improved through the cultivation of salt-tolerant trees and the application of organic manures. Trees such as Acacia, Neem, Prosopis, Tamarix, and Albizzia enhance soil permeability, add organic matter, and help replace exchangeable sodium with calcium, thereby improving soil health. Forest vegetation also promotes microbial activity and improves the microclimate. Farmyard manure (FYM) is an effective organic amendment; applying 10 tonnes of FYM with 15 tonnes of Sesbania leaves per hectare has been shown to increase paddy yields almost as effectively as 30 tonnes of Sesbania green manure.

### 4. Biological Methods

Bio remediation of saline soil Bioremediation is a sustainable approach in order to reduce and alleviate the toxic effect of salinity. Two different types in bio remediation are: • **Phytoremediation** • **Microbial remediation**

#### Phytoremediation

Phytoremediation involves using plant species to diminish the concentration of the salts or contaminants in the soil. Plant species like halophytes, hyper accumulating plants, salt tolerant and transgenic salt tolerant plants used for phytoremediation of saline soil. ex., Tamix chinensis, Lycium chinense, Gossypium hirsutum. There are



three types of halophytes: (a) salt excluding – filters the salt by specially adoptive root system, ex. *Rhizophora muaneta*; (b) salt excreting – regulate the plant internal cell physiology, ex. *Avicennia officinalis*; salt accumulating – accumulating salts in cells and tissues of halophytes, ex. *Sonneratia apetala*

### Microbial remediation

Various salt tolerant rhizosphere microbial community (Halophills) which remediate the saline soils. Mechanism of microbial tolerant involves

(i) maintains cytoplasmic ionic content equal to the medium, (ii) concentrating solutes for create osmotic balance, (iii) after cell physiology restrict or control movement of water both inside and outside of the cytoplasm . *Halobacillus* sp., *Bacillus gibsonii*, *Halobacterium salinarum*, *Staphylococcus succinus*, *Zhihengliuella halotolerans*, *Oceanobacillus oncorhynchi* are the examples of halotolerent bacteria

### Conclusion

Soil salinity is a major constraint to sustainable agriculture, adversely affecting soil health, crop productivity, and environmental quality. Effective reclamation requires an integrated approach combining physical, chemical, biological, and agronomic practices. Conventional methods such as gypsum application, drainage, and leaching remain fundamental, while biological approaches including phytoremediation, microbial remediation, and organic amendments provide environmentally sustainable solutions for improving soil fertility and resilience. Efficient irrigation and drainage management are equally important for preventing secondary salinization and ensuring long-term productivity. The integration of these strategies, supported by site-specific management and modern monitoring technologies, offers a sustainable pathway for reclaiming salt-affected soils and enhancing agricultural productivity under changing climatic conditions.

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# Role of Bamboo in Restoring Degraded Lands

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Land degradation is one of the critical environmental issues globally and can impact soil quality, biodiversity, water availability, and agricultural productivity. The use of bamboo as a nature-based solution for remediation of degraded lands has been recognized owing to its fast growth rate, dense root and rhizome system, high biomass yield, and adaptation to different environments. This paper will discuss how bamboo can be used for control of soil erosion, improvement of soil quality, water conservation, carbon sequestration, enhancement of biodiversity, and rehabilitation of mined and degraded lands. Also, this paper will focus on socio-economic importance of bamboo, species for rehabilitation, success stories of rehabilitation, and challenges with bamboo-based rehabilitation.

## Introduction

The degradation of the land is one of the most urgent environmental issues being faced by the entire world today. Land degradation can be defined as the process in which there is degradation of the quality of the land because of various natural factors and human intervention that leads to a decline in the productivity of the land, degradation of the soil and loss of vegetation as well as reduction in biological diversity (Eswaran et al., 2019). As per the global estimates, billions of hectares of land are degraded owing to deforestation, mining, overgrazing, soil erosion, shifting cultivation, industries, and agriculture (Hossain et al., 2020). In India, huge areas of forests, waste lands, ravines, mined lands, and degraded agricultural lands need to be restored (Jinger et al., 2023). Degraded land restoration is key to biodiversity conservation, soil improvement, provision of water supply, climate change mitigation, and sustainable development (Arneth et al., 2021). Among many nature-based solutions that exist, bamboo has come out as one of the most attractive species for ecological restoration (Haida et al., 2026). Known as the "green gold" due to its significant ecological and economic importance, bamboo is a fast-growing woody grass that can survive in

different environmental settings (Irawan et al., 2025). Due to its huge root and rhizome systems, fast-growing characteristics, high biomass accumulation potential, and soil improvement properties, bamboo stands out as the most suitable species for restoration purposes (Rathour et al., 2022).

## Why Bamboo?

Bamboo exhibits several distinctive attributes that make it very appropriate for use in the implementation of land restoration projects (Nforinkah et al., 2023). The first attribute is the unusually rapid growth of bamboo plants. Certain species of bamboo grow at the rate of several centimeters a day, thus facilitating the quick formation of vegetation cover on bare lands (Mera and Xu, 2014). This fast growth ensures better protection of soils from exposure and speeds up the process of environmental rehabilitation. Besides, bamboo creates a very extensive root and rhizome system that strongly connects soil particles to each other. Such a subterranean system allows stabilizing the condition of loose soils, preventing their erosion and the development of landslides in hilly landscapes (Acharya, 2018). What is more, after cutting, bamboo re-sprouts from the remaining rhizome without the need for replanting; therefore, it is quite a renewable



natural resource (Haida et al., 2026). Finally, the adaptability of bamboo plants is another benefit that makes them very appropriate for restoration purposes. Namely, bamboo grows in a variety of climatic zones, ranging from tropical and subtropical areas to certain temperate ones (Ahmad et al., 2021). Many plants are able to survive harsh environmental conditions such as drought, infertile soils, and disturbed areas, thus enabling them to grow in places where no other tree species can survive. Additionally, bamboo is known to produce high amounts of biomass and leaves that ultimately help in adding organic matter to the soil and improving its properties (Rathour et al., 2022).

## **How Bamboo Restores Degraded Lands**

### **Soil Erosion Control**

Soil erosion is one of the major factors leading to land degradation. The top fertile soil is washed away by heavy rains and wind, leading to reduced fertility of the land as well as increased sediments in rivers and reservoirs (Issaka and Ashraf, 2017). Bamboo is very effective in controlling soil erosion due to its thick root and rhizome network that helps in binding the soil (Acharya, 2018).

### **Improvement of Soil Fertility**

The role of bamboo in improving the quality of soil is significant because bamboo constantly deposits its fallen leaves, branches, and other organic matter on the surface of the soil (Tripathi et al., 2024). In the process of decomposition of this litter, organic carbon and nutrients are released into the soil, increasing its fertility (Tiessen et al., 1994). An increased amount of organic matter positively affects soil structure and increases nutrient cycling (Mohammadi et al., 2011).

### **Water Conservation**

Well-grown bamboo plantation can enhance the soil's capacity to take up and hold water (Ben-zhi et al.,

2005). Through the formation of pores within the soil through its root system, it can help enhance water percolation into the soil while decreasing any surface run-off (Patra et al., 2022). This will help recharged ground water resources, soil moisture conservation, and mitigate floods when there is heavy rainfall.

## **Carbon Sequestration and Climate Change Mitigation**

The efficiency of bamboo as a carbon sink has been well known owing to its fast growing nature and its capacity for carbon sequestration (Zhou et al., 2011). The plants take in large amounts of carbon dioxide from the atmosphere and retain it in their stems, branches, foliage, and rhizomes (Yiping et al., 2010). This process of sequestration and reduction of greenhouse gases helps in combating global warming as well as ecosystem restoration (Dutta et al., 2025).

## **Biodiversity Conservation**

Bamboo plantations provide ideal living conditions for many kinds of birds, insects, reptiles, mammals, and microorganisms (Dutta et al., 2025). As the degraded lands rehabilitate, the diversity of species increases, resulting in more stable ecosystems. In addition, bamboo can be used as a source of food for wildlife, and provides habitat for pollinators, which is vital for the existence of ecosystems (SijiMol et al., 2016).

## **Restoration of Mined and Wastelands**

Mine reclamation often results in soils that are highly degraded, infertile, and with little vegetation cover. Bamboos have shown great promise in the restoration of mine soils due to their versatility, easy establishment, and soil binding properties (Nfornkah et al., 2023). They stabilize degraded soils, increase organic matter content, and pave way for successional processes to take place.





## Socio-Economic Benefits

Apart from its ecological importance, bamboo offers a wide range of economic activities that directly benefit the rural communities (Wang et al., 2021). Bamboo canes are employed for construction, furniture making, craftwork, fences, scaffolds, basketry, paper and pulp, incense sticks, engineered bamboo products, and bioenergy (Ahmad et al., 2025). Bamboo shoots when young can be utilized as edible vegetables, and thus offer an additional source of income for many people (Chongtham et al., 2011). Bamboo value chain also offers employment in nursery planting, plantations, harvesting, processing, manufacture of various products, transport and marketing of products (Chihongo et al., 2000). Bamboo-based small-scale industries play a vital role in rural development and women's self-help groups (Kumar et al., 2026). Being a regenerating material, bamboo continuously and sustainably supplies raw materials without the need for replantation each time (Haida et al., 2026). Therefore, bamboo rehabilitation projects improve degraded ecosystems as well as enhance livelihood and green economic development.

## Suitable Bamboo Species for Bamboo-Based Restoration

The choice of suitable bamboo species is an important factor in ensuring the success of the bamboo-based restoration process.

**Some of the species which are usually recommended include:**

*Dendrocalamus strictus* – Drought resistant and ideal for drylands, wastelands and stony soils.

*Bambusa bamboos* – Ideal for soil conservation, river bank stabilization and degraded forests restoration.

*Bambusa balcooa* – An extremely sturdy species that grows quickly, making it ideal for biomass and land reclamation.

*Dendrocalamus asper* – Produces plenty of biomass and ideal for fertile and moderately degraded lands.

*Bambusa tulda* – Ideal for moist areas and has been widely used in ecological restoration and for other commercial uses.

Factors to consider when choosing suitable bamboo species include: Rainfall, soil, temperature, altitude, water and restoration objectives.

## Success Stories

Several successful restoration programmes using bamboo show the potential of this amazing plant (Singh et al., 2020). Bamboo is being planted successfully in many mine sites in eastern and central India to improve soil conditions and stabilize the dumps created by mining activities (Sawarkar et al., 2025). In a few years, bamboo plantations have helped in stopping soil erosion, increase in soil organic matter content and regeneration of indigenous vegetation. Bamboo plantations are also being undertaken along the banks of rivers and streams to stop soil erosion and stabilize the banks. The roots of bamboo help in protecting the banks of the rivers and streams during floods and also in maintaining the quality of the water (Ben-zhi et al., 2005). Bamboo plantations undertaken by communities in many states have rejuvenated the village lands and generated incomes from bamboo harvest, crafts and processed products (Kumar et al., 2026).

## Challenges

1. Even though it has numerous benefits, restoration using bamboo needs careful planning and management.
2. One of the biggest problems encountered in many areas is the availability of good planting material.



Proper choice of species is necessary to ensure successful implementation.

3. The plantation at the young age needs protection from animals grazing, fire, and any other human activities. Irrigation and removal of weeds increase the chances of success.

4. Success of this process will also depend upon proper harvesting and monitoring along with community participation.

### Conclusion

Bamboo represents a very promising natural solution for the rehabilitation of degraded lands because of its rapid growth, large root system, ability to produce biomass, and adaptation to different conditions. The plant has great importance in controlling soil erosion, soil fertility, water conservation, carbon sequestration, biodiversity improvement, and many other aspects. At the same time, bamboo can be used as an important source of economic goods and support people's livelihood in rural communities. Nevertheless, effective bamboo reclamation needs proper selection of the plant, good planting materials, management, and involvement of communities.

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# Transmission of infectious diseases between animals and farms

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India is an agrarian country and still a major part of the population is dependent on agriculture and livestock rearing for their livelihood. Therefore, the health of livestock is considered directly proportional to the income of livestock farmers. Infectious diseases spread fast among the animals and farms resulting into reduced productivity of the animal. Moreover, the diseases responsible for causing abortion and mortality in animals result in significant economic losses for farmers. Disease control and prevention are always more cost-effective than treating the disease. Infectious diseases are caused by microorganisms like bacteria, viruses, fungi and parasites. These microorganisms spread through direct contact between animals, through contaminated feed and water, etc. Introduction of infected animal without proper screening and quarantine is one of the major causes of outbreaks of disease in a new farm or place. Effective prevention strategies include maintaining farm hygiene, following strict biosecurity measures, vaccination, quarantine of newly purchased animals, balanced nutrition, and isolation of sick animals, vector control, along with timely veterinary intervention. Disease prevention is more economical and effective than treatment and plays a vital role in protecting animal health, and livelihood of the farmers.

## Introduction

Rural livelihood depends on either agriculture or livestock farming in India. Marginal and small-scale farmers majorly depend on livestock farming for food production. Infectious diseases impacting the health of animals come as a biggest challenge for these farmers every year. Disease outbreaks lead to reduced milk, meat, and egg production, poor weight gain, abortions and infertility, increased treatment costs, mortality and trade restrictions. In severe outbreaks, farmers may lose entire flocks or herds.

These disease-causing microorganisms are invisible to the naked eye, yet they transmit among animals, through contaminated materials, and the environment. This article describes the common routes of disease transmission on livestock farms and the preventive measures farmers should adopt to protect animal health. Infectious diseases are caused by microorganisms such as bacteria (e.g., *Brucella*, *Salmonella*), viruses (e.g., foot and mouth disease virus, Newcastle disease virus), parasites (e.g.,

coccidia, worms) and fungi (e.g., ringworm fungi). These organisms can multiply inside animals and spread to healthy animals under favourable conditions like stress and poor nutrition.

Once one infected animal or any other carrier of disease causing pathogen enters the farm, it may spread rapidly if proper biosecurity measures are not followed. The conditions that favour the disease transmission are:

- Close contact between animals and sharing feed and water troughs
- Movement of farmers and workers between animal sheds
- Use of common equipment without proper sanitisation for multiple animals
- Poor hygiene and overcrowding





## Common ways of infectious disease transmission in animals

Direct contact is one of the most common modes of disease transmission. A healthy animal coming in contact with secretion and excretions of infected animal, acquire the infection. The common diseases that spread by direct contact are foot and mouth disease (FMD), lumpy skin disease (LSD), Newcastle disease in poultry, etc.

1. Certain microorganisms spread through droplets released during coughing, sneezing, or breathing, causing respiratory infections in livestock. Airborne spread is more common in overcrowded sheds, poorly ventilated houses and dusty farm environments.
2. Contaminated feed and drinking water are major sources of disease transmission. Dirty water troughs, moldy feed, faecal contamination or rodent infestation are the common sources of feed and drinking water contamination. The diseases associated with are salmonellosis, coccidiosis, botulism, etc.
3. Many disease-causing organisms are shed through the faeces and urine of infected animals and their direct or indirect ingestion by healthy animals becomes a source of infection. Diseases spread through faeces and urine is Johne's disease, Leptospirosis, coccidiosis and parasitic infections. Additionally, the wet and dirty farm floors increase the survival of pathogens in the environment resulting into long term survival of the pathogens.
4. Vectors are living organisms that carry pathogens from one animal to another. Common vectors associated with animal diseases are mosquitoes, ticks, fleas, flies, and rodents. And the diseases spread by vectors are Leptospirosis, Bluetongue and Tick fever. Also, flies and rodents mechanically transfer bacteria from infected waste to feed and water.
5. Contaminated equipment's like milking machine, needles, feeding utensils, farm worker's boots and clothing and vehicles can act as source of pathogen transfer. If not disinfected properly, infections may spread between animals and farms.
6. Purchase of animals from markets or unknown sources without screening for infectious diseases and isolation of animal is a major reason for disease outbreaks in farms. Newly introduced animals may carry infections, shed pathogens without symptoms and introduce diseases not previously present on the farm. Hence, the new animals should not be mixed with the other animals in the herd, without quarantine of at least 2-3 weeks.
7. Certain reproductive diseases like brucellosis, campylobacteriosis, trichomoniasis, etc., spread during mating or during artificial insemination with infected semen. These infections can cause infertility, repeat breeding, and abortions.
8. Some infections pass from mother to offspring during pregnancy, birth, or milk feeding like brucellosis, bovine viral diarrhoea (BVD) and mycoplasmal infections. Young animals have weaker immunity and are highly susceptible to infections.
9. Stress is also one of the major factors that weakens the immune system and increases disease susceptibility. The common stress factors are overcrowding, heat, poor nutrition, sudden weather changes and transportation.

## How farmers can prevent disease spread?

1. Cleaning the sheds, disinfecting the equipments used and discarding the manure and other waste regularly.



2. Restricting the visitors, allowing the entry in the farm through footbaths containing disinfectant like sodium hypochlorite, ammonium salts, etc.
3. Regular vaccination against major infectious diseases to protect animals from various infectious diseases.
4. Isolation of sick animals from healthy ones, as soon as the animal shows signs of a disease.
5. Strict control of insects and rodents in the farm to avoid vector-borne disease.
6. Quarantine of purchased animals for at least 2-3 weeks before introducing to the herd
7. Veterinary practitioner's advice for early diagnosis and preventing severe outbreaks and economic losses.
8. Most importantly, providing balanced and sufficient nutrition to build immunity in the animal.

### Conclusion

Control and preventive measures taken up by the farmers can keep the animals healthy and safe from the infectious diseases to a major extent. Understanding of common diseases prevalent in the local area or the region is the first and foremost step taken up by the farmer. Knowing the ways of transmission of disease can help introduce the specific biosecurity measures by the farmer, followed by proper vaccination. Along with this, measures like good hygiene, isolation of sick animal, and timely consultation with veterinary consultant should be

followed. Attending “pashu-palan melas” or trainings organized by state universities or Kisan vigyan kendras (KVKs) for the upgradation of knowledge can help a farmer keep his animals healthy and productive. Protecting animal health at the first place can prevent the cost associated with treatment or the loss of the animal.

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# Assessment of greenhouse gas emissions from crop fields: methods and implications

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Greenhouse gas (GHG) emissions from field crops are a major contributor to global climate change, particularly through the release of Carbon dioxide (CO<sub>2</sub>), Methane (CH<sub>4</sub>), and Nitrous oxide (N<sub>2</sub>O). Due to which accurate and reliable measurements of these gases is highly essential for evaluating the environmental impact. Generally, there are two major approaches used in the agricultural field to estimate the GHGs emission and they are Closed chamber method and Micrometeorological techniques. The closed-chamber method involves enclosing a portion of the crop area to directly measure gas concentrations over time which offers high precision at a small scale. In contrast, micrometeorological methods such as the eddy covariance system provide continuous, non-intrusive, and large-scale measurements of gas fluxes, making them suitable for real-time and long-term monitoring. Therefore, this article discusses the principles, advantages, and limitations of both methods and emphasizes their complementary roles in quantifying GHG emissions from various cropping systems for sustainable agricultural management.

## Introduction

Agriculture plays a key role in climate change, contributing significantly to global Greenhouse gas (GHG) emissions, towards the enhanced global warming (IPCC 2007). Field crops such as rice, wheat, maize, and barley are essential for global food security, but they also contribute significantly to GHG emissions. These emissions, primarily in the form of Carbon dioxide (CO<sub>2</sub>), Methane (CH<sub>4</sub>), and Nitrous oxide (N<sub>2</sub>O), are released through various agricultural practices, such as fertilizer application, soil management, irrigation, and crop residue decomposition. As the world faces the dual challenges of feeding an expanding population while mitigating the impacts of climate change, understanding and quantifying GHG emissions from field crops is becoming increasingly critical. Prominently, GHG emissions from field crops vary depending on factors such as soil type, crop species, climate, farming practices, and management techniques. By measuring and monitoring these emissions, researchers and policymakers can identify the primary sources of emissions, evaluate the

effectiveness of mitigation measures, and create strategies to minimize the global warming potential. Notably, field crop production is responsible for significant emissions of CH<sub>4</sub> and N<sub>2</sub>O. However, CH<sub>4</sub> is released in flooded rice paddies due to anaerobic microbial activity in the soil, while N<sub>2</sub>O is primarily emitted from nitrogen-based fertilizers. Additionally, soil disturbances from tilling and other farming practices lead to the release of CO<sub>2</sub> stored in the soil. As agriculture is directly linked to the global carbon cycle, understanding these emission dynamics is crucial for managing and reducing the environmental impact caused by agricultural practises. In recent years, climate resilient livestock practices have gained importance as sustainable approaches to reduce GHG emissions and improve productivity. Practices such as improved feeding management, rotational grazing, scientific manure management, sustainable soil and water management, improved feed conversion efficiency and climate-smart risk management can significantly reduce environmental impacts while enhancing farmer resilience and resource use efficiency (Ajmal and Parapurath, 2026). In this context, measuring



GHG emissions from field crops provide insights into the effectiveness of agricultural practices in minimizing climate change impacts. Therefore, accurate measurements can help farmers, researchers, and policymakers design targeted mitigation strategies that reduce emissions while maintaining or improving crop yields. Furthermore, GHG emission data can facilitate participation in carbon offset programs and enable agricultural systems to adapt to changing environmental conditions. Taking all these things into consideration, this article explores the various methods used to measure GHG emissions from field crops and examines the sources and hotspots of emissions.

### Emission hotspots in field crops

- i. **Rice fields:** Major source of CH<sub>4</sub> due to anaerobic conditions
- ii. **Fertilized soils:** High N<sub>2</sub>O emissions from nitrogenous fertilizers
- iii. **Tilled lands:** Release CO<sub>2</sub> from disturbed soils

### Why measure GHGs emission?

- i. Identify major emission sources in cropping systems
- ii. Design climate-smart practices to reduce emissions
- iii. Support carbon credit initiatives and eco-friendly certifications
- iv. Guide policymakers in forming effective environmental regulations

### Measurement of GHGs emission

Quantification of GHGs emission is not very difficult, but high spatial and temporal variations at local scales make it difficult. However, there are 2 methods to measure GHGs emission viz., Closed-

chamber methods and Micrometeorological techniques.

### Closed-chamber Method

Chamber method is one of the most accessible techniques for measuring greenhouse gas emission. Gas flux is collected by static chambers installed in the field. There are two parts in the static chamber (anchor or base and chamber). Anchor is made up of thin-walled stainless steel to minimize physical disturbance upon insertion. Whereas, chambers are fabricated with non-reactive materials. It has two ports for temperature assessment and gas sampling. Initially, anchors are installed at 10 cm into the ground at least 24 hours prior to the first flux measurement and packed well around the sides because they can affect the soil microclimate. Secondly, chamber is kept upside down upon the base at the time of gas sampling. Generally, plants are present inside the chambers during gas sampling. So, before sampling, the presence of water in the rim of base is essential. Additionally, the flood water level both inside and outside the base is noted, soil temperature is recorded and chamber temperature is noted immediately after sampling. The sampling is performed by inserting a polypropylene syringe into the chamber septa and the gas sample is removed slowly. Generally, sampling is done in three times at fifteen minutes interval viz., 0, 15, and 30 minutes after the deployment of chamber. Typically, 20 ml sample is removed and transferred to a previously evacuated 15 ml glass vial sealed with grey butyl rubber septum. The excess gas is injected into the evacuated vial to produce an overpressure and this overpressure facilitates the subsequent removal of gas sample for analysis. Finally, the gas samples are analysed using Gas Chromatography (GC).

### Collection of gas samples

For collection of gas samples acrylic/perspex chambers of 50 cm × 30 cm × 100 cm size (according to experiment i.e., type and stage of the crop growth)



is placed on the Aluminium channel inserted 10 cm inside the soil and the channels filled with water to make the system air-tight. Silicon septum is fitted at the top of the chamber to collect gas samples and the air inside the chamber is homogenized with the battery-operated fan or air circulation pump with an air displacement of 1.5 Lmin<sup>-1</sup>. The gas samples are collected with 20-50 mL syringe with the help of 24-gauge hypodermic needle at an interval of 0, 0.15 and 0.30 hrs. After drawing sample, the syringe should be made air tight with three way stop cock. Finally, the air temperature and head space volume inside the box required for calculation of GHGs flux should be recorded.

### Analysis of gas samples

Gas concentrations are measured using a Gas Chromatograph (GC), which separates and detects specific gases like CH<sub>4</sub> and N<sub>2</sub>O. For methane, Flame Ionization Detector (FID) burns the sample and measures ions formed in the flame, with the result shown as a peak on the computer (only substances that can ionize in the flame are detected). Whereas, N<sub>2</sub>O is analysed using Electron Capture Detector (ECD), which uses a radioactive electrode to produce electrons, and then measures how much the nitrous oxide captures these electrons. However, both techniques rely on specialized columns and controlled temperatures to ensure that gases are separated and detected accurately for yielding precise measurements that are recorded and displayed using dedicated software.

### Closed-chamber method to calculate the flux

The flux of methane and nitrous oxide is calculated using the following equations.

$$\text{Cross-sectional area of the chamber (m}^2\text{)} = A$$

$$\text{Headspace (m)} = H$$

$$\text{Volume of headspace (L)} = 1000 \times AH$$

$$\text{CH}_4 \text{ concentration at 0 time } (\mu\text{L L}^{-1}) = C_o$$

$$\text{CH}_4 \text{ concentration after time } t (\mu\text{L L}^{-1}) = C_t$$

$$\text{Change in concentration in time } t (\mu\text{L L}^{-1}) = (C_t - C_o)$$

$$\text{Volume of CH}_4 \text{ evolved in time } t (\mu\text{L}) = \frac{(C_t - C_o) \times 1000}{AH}$$

$$\text{When } t \text{ is in hours, then flux (mL m}^{-2} \text{ h}^{-1}\text{)} = \frac{((C_t - C_o) \times 1000}{AH) / (A \times t)}$$

Now 22.4 mL of CH<sub>4</sub> is 16 mg at STP

Hence,

$$\text{CH}_4 \text{ flux} = \frac{((C_t - C_o) / t) \times H \times 16}{22.4 \times 10000 \times 24} \text{ mg ha}^{-1} \text{ d}^{-1}$$

$$\text{N}_2\text{O flux} = \frac{((C_t - C_o) / t) \times H \times 44}{22.4 \times 10000 \times 24} \text{ mg ha}^{-1} \text{ d}^{-1}$$

### Micrometeorological method

Micrometeorological Methods are advanced techniques used to measure GHG emissions from agricultural fields on a larger scale and over extended periods. Gas fluxes are typically measured for an area which is 1-10 km<sup>2</sup> to several million ha, and fluxes are measured continuously, not just while chambers are in place. Unlike chamber methods, which focus on small, isolated areas, micrometeorological approaches capture gas fluxes across entire fields or ecosystems without disturbing the natural environment. These methods rely on precise measurements of gas concentrations and atmospheric conditions (like wind speed and temperature) at multiple heights above the crop canopy by using sensors mounted on towers. As a result, micrometeorological methods can capture air movement, gas composition, flux rates and directions based on diffusion, and turbulence. This allows researchers to continuously monitor real-time emissions of gases like CO<sub>2</sub>, CH<sub>4</sub>, and N<sub>2</sub>O).





Micrometeorological methods are especially useful in large-scale field studies, providing reliable, long-term data that help understand the effects of weather and crop type on GHG emissions. However, these methods require expensive equipment, technical expertise, and intensive data processing, making them more suitable for research and monitoring purposes than routine farm use. Hence, this method is less selected when compared to Closed chamber technique,

### Necessary mandates while measuring the GHGs

- i. While collecting the gas samples from crop, the chamber should be placed on the soil in such a way that 4-6 plants are inside the chamber
- ii. In upland irrigated/rainfed crops the chamber should be placed in between the rows/plants to collect the samples
- iii. The height of the chamber should be more than 30 cm
- iv. The chamber headspace gas concentration at zero hour should be measured accurately.
- v. Air samples should be taken in very short time to observe a measurable increase in headspace gas concentration. Longer chamber deployment durations may result in negative impacts.
- vi. To reduce the uncertainty arising out of spatial variability, a greater number of chambers should be deployed. Longer period of sampling results in better precision however too long period may yield sampling artifacts.
- vii. To avoid the diurnal variation the gas samples from the field should be collected in definite

time span in day throughout the cropping season, preferably during 09:00-11:00 and 15:00-17:00 hours.

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## Biochar-Integrated Constructed Wetlands: A Sustainable Nature-Based Solution for Wastewater Treatment

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Increasing wastewater generation due to urbanization, agriculture, and industrial activities demands sustainable and affordable treatment technologies. Biochar-integrated constructed wetlands (BC-CWs) have emerged as an innovative nature-based solution that enhances the efficiency of conventional constructed wetlands by incorporating biochar as a functional substrate. Owing to its high porosity, large surface area, and excellent adsorption capacity, biochar improves the removal of organic matter, nutrients, heavy metals, and emerging contaminants while providing a favorable habitat for beneficial microorganisms. This integrated system combines physical filtration, chemical adsorption, and biological degradation to achieve superior treatment performance with minimal energy and operational costs. In addition to improving water quality, BC-CWs promote resource recovery, carbon sequestration, wastewater reuse, and the productive utilization of agricultural residues. Their simplicity, scalability, and environmental benefits make them well suited for decentralized wastewater management, supporting sustainable development, climate resilience, and the objectives of the Viksit Bharat 2047 mission.

### Introduction

Water is one of the most valuable natural resources, supporting human health, agriculture, aquaculture, industries, and ecosystems. However, rapid urbanization, industrial expansion, intensive agricultural practices, and population growth have significantly increased the generation of wastewater worldwide. According to the United Nations, more than 80% of wastewater generated globally is discharged into the environment without adequate treatment, leading to severe degradation of freshwater ecosystems, groundwater contamination, biodiversity loss, and public health concerns (UN-Water, 2021).

Conventional wastewater treatment technologies have played a crucial role in improving water quality, but their installation and operational costs remain prohibitively high for many rural and peri-urban communities. Moreover, these systems require skilled manpower, continuous energy supply, and sophisticated infrastructure, making them difficult to implement in decentralized regions. These

limitations have encouraged researchers to explore environmentally friendly, low-cost, and sustainable alternatives capable of providing efficient wastewater treatment while minimizing environmental impacts (Vymazal, 2010).

Among various nature-based solutions, constructed wetlands have emerged as one of the most promising technologies. These engineered ecosystems mimic the purification processes occurring in natural wetlands by utilizing aquatic plants, microorganisms, and filtration media to remove pollutants from wastewater. Despite their ecological and economic advantages, conventional constructed wetlands often show limited efficiency in removing nutrients, heavy metals, pharmaceuticals, pesticides, and other emerging contaminants. To overcome these limitations, researchers have recently introduced biochar into constructed wetland systems, creating an innovative technology known as Biochar-Integrated Constructed Wetlands (BC-CWs). This integrated approach combines the adsorption capacity of biochar with the biological and ecological



functions of constructed wetlands, significantly improving pollutant removal efficiency while promoting sustainability and climate resilience (Mohan et al., 2014; Enaime et al., 2020).

### Challenges of Wastewater Management

Increasing wastewater generation has become one of the most pressing environmental issues of the twenty-first century. Domestic sewage, industrial effluents, livestock waste, and agricultural runoff contain large quantities of organic matter, nutrients, pathogens, heavy metals, antibiotics, pesticides, and various toxic chemicals. When discharged untreated into rivers, lakes, wetlands, and coastal waters, these pollutants deteriorate water quality and threaten aquatic biodiversity.

Excessive nitrogen and phosphorus entering aquatic ecosystems stimulate harmful algal blooms, resulting in eutrophication and oxygen depletion. Heavy metals accumulate within aquatic food chains, posing serious health risks to fish, wildlife, and humans. Similarly, emerging contaminants such as pharmaceuticals, personal care products, antibiotics, and microplastics are increasingly detected in freshwater bodies, where they affect aquatic organisms even at trace concentrations (Kadlec and Wallace, 2008).

Climate change further intensifies wastewater management challenges by increasing the frequency of floods, droughts, and extreme weather events that overwhelm conventional treatment facilities. Therefore, resilient, decentralized, and environmentally sustainable treatment technologies have become essential for achieving long-term water security.

### Constructed Wetlands for Water Purification

Constructed wetlands are engineered treatment systems designed to imitate the natural purification functions of wetlands. Wastewater flows slowly through planted beds containing gravel, sand, or

other porous media where physical, chemical, and biological processes collectively remove contaminants. The treatment process involves several simultaneous mechanisms. Suspended solids are removed through sedimentation and filtration. Organic pollutants are decomposed by microorganisms attached to the substrate and plant roots. Aquatic plants absorb nutrients, while microbial communities convert ammonia into nitrate and subsequently into harmless nitrogen gas through nitrification and denitrification.

Constructed wetlands require minimal energy input, have low maintenance requirements, and produce comparatively less sludge than conventional treatment plants. Their aesthetically pleasing appearance and ability to support biodiversity further enhance their environmental value. Nevertheless, their efficiency may decline when treating wastewater containing high nutrient concentrations, toxic metals, pharmaceutical residues, or emerging contaminants. This limitation has encouraged the search for enhanced substrate materials capable of improving treatment performance.

### Biochar for Environmental Remediation

Biochar is a stable carbon-rich material produced through the pyrolysis of biomass under oxygen-limited conditions. Agricultural residues, forestry wastes, coconut shells, rice husks, bamboo, sugarcane bagasse, and other organic wastes can all serve as feedstocks for biochar production. The exceptional properties of biochar arise from its highly porous structure, extensive surface area, abundant functional groups, and excellent adsorption capacity. These characteristics enable biochar to retain nutrients, adsorb heavy metals, capture organic pollutants, and provide ideal habitats for beneficial microorganisms (Lehmann and Joseph, 2024). Unlike activated carbon, biochar can be produced locally from agricultural residues at relatively low cost, making it especially suitable for developing countries. Besides improving wastewater treatment,



biochar contributes to carbon sequestration because it remains stable in the environment for decades or even centuries, thereby reducing atmospheric carbon dioxide concentrations.

### Biochar-Integrated Constructed Wetlands

Biochar-integrated constructed wetlands represent the next generation of sustainable wastewater treatment systems. Instead of relying solely on conventional gravel and sand, biochar is incorporated into the wetland substrate either as a partial replacement or as a supplementary filtration medium. The integration creates multiple treatment pathways that operate simultaneously. Wastewater entering the system first passes through the porous biochar layer, where suspended particles are physically trapped. Organic contaminants, nutrients, and toxic chemicals are subsequently adsorbed onto the extensive internal surface of biochar.



Figure1. Biochar-Integrated Constructed Wetlands for wastewater treatment

The porous architecture also provides abundant attachment sites for beneficial microorganisms. These microbial biofilms degrade dissolved organic compounds while converting nitrogen compounds through biological nitrification

and denitrification. Furthermore, aquatic plants transport oxygen into the root zone, stimulating aerobic microbial activity and enhancing nutrient cycling throughout the wetland. Together, these physical, chemical, and biological interactions significantly improve pollutant removal compared with conventional constructed wetlands, resulting in higher treatment efficiency and improved water quality (Enaime et al., 2020).

### Working Mechanism of Biochar-Integrated Constructed Wetlands

The superior performance of BC-CWs results from the interaction of several complementary mechanisms. Initially, suspended solids are physically filtered by the porous substrate. Fine particles become trapped within the interconnected pore network of biochar, thereby reducing turbidity and improving water clarity. Simultaneously, adsorption becomes a dominant removal process. Organic compounds, ammonia, phosphate, heavy metals, dyes, antibiotics, pesticides, and various emerging contaminants adhere to the biochar surface through electrostatic attraction, ion exchange, surface complexation, and pore filling.

Microbial degradation constitutes another major mechanism. The enormous surface area of biochar supports diverse microbial communities that decompose biodegradable organic matter. These microorganisms convert ammonia into nitrate and subsequently transform nitrate into nitrogen gas, thereby reducing total nitrogen concentrations. Plant uptake also contributes significantly to nutrient removal. Wetland vegetation absorbs nitrogen and phosphorus for growth while stabilizing the substrate and improving oxygen transport within the rhizosphere. Collectively, these processes create a highly efficient treatment system capable of addressing multiple categories of pollutants simultaneously.





## Major Advantages of Biochar-Integrated Constructed Wetlands

One of the greatest strengths of BC-CWs is their substantially enhanced treatment efficiency. Numerous studies have reported improved removal of biochemical oxygen demand (BOD), chemical oxygen demand (COD), total suspended solids, ammonia, nitrate, phosphate, heavy metals, dyes, and pharmaceutical residues compared with conventional wetlands. The high adsorption capacity of biochar enables efficient capture of pollutants that are otherwise difficult to remove. Its porous structure also provides a stable habitat for microbial communities, promoting continuous biological degradation.

From an economic perspective, BC-CWs require relatively low capital investment and consume very little energy because treatment relies primarily on natural processes. Operational and maintenance costs are considerably lower than those associated with conventional wastewater treatment plants. The technology also promotes circular economy principles by converting agricultural residues into valuable biochar rather than allowing them to be openly burned or discarded. Farmers can transform crop waste into a useful environmental resource while simultaneously reducing pollution.

An equally important benefit is carbon sequestration. Biochar stores stable carbon within the treatment system for long periods, helping mitigate climate change by reducing greenhouse gas emissions. Improved wastewater treatment additionally lowers methane and nitrous oxide emissions commonly associated with poorly managed wastewater systems. BC-CWs are highly adaptable and scalable. They can be implemented for households, villages, institutions, fish farms, industries, and municipal wastewater treatment facilities, making them suitable for decentralized sanitation systems.

## Applications Across Multiple Sectors

Biochar-integrated constructed wetlands have broad applications in domestic, industrial, agricultural, and aquaculture sectors. In rural communities, they provide affordable decentralized treatment of household wastewater while enabling safe water reuse for irrigation. In urban areas, they can complement centralized treatment plants by polishing treated effluents before discharge. Agricultural runoff containing fertilizers and pesticides can be effectively treated, thereby reducing nutrient loading into nearby rivers and reservoirs. Industrial wastewater containing dyes, metals, and organic chemicals may also benefit from biochar adsorption before final discharge.

Aquaculture represents another promising application. Fish farming generates nutrient-rich wastewater containing uneaten feed, suspended solids, ammonia, and organic matter. BC-CWs can substantially improve water quality before reuse or discharge, contributing to sustainable aquaculture and reducing environmental impacts.

## Contribution Towards Viksit Bharat 2047

The Government of India's Viksit Bharat 2047 vision emphasizes sustainable development, environmental protection, technological innovation, and resource efficiency. Biochar-integrated constructed wetlands align remarkably well with these national priorities.

The technology strengthens water security by enabling wastewater recycling and reducing dependence on freshwater resources. It supports improved sanitation by providing decentralized treatment systems suitable for villages and peri-urban settlements where centralized infrastructure is unavailable. The innovation advances the circular economy by converting agricultural residues into valuable biochar, transforming waste into wealth while reducing biomass burning. Through long-term carbon storage and reduced greenhouse gas





emissions, BC-CWs contribute directly to India's climate action commitments and net-zero aspirations.

The treated water can be safely reused for irrigation, aquaculture, landscaping, and groundwater recharge, thereby supporting sustainable agriculture and fisheries. Since biochar feedstocks are locally available, the technology encourages Atmanirbhar Bharat by minimizing dependence on imported treatment materials and expensive technologies. BC-CWs represent an outstanding example of green technology development, demonstrating how nature-based innovations can address environmental challenges while promoting economic sustainability.

### Future Perspectives

Although biochar-integrated constructed wetlands have demonstrated remarkable potential, further research is required to optimize biochar production conditions, feedstock selection, hydraulic design, and long-term operational performance. Future studies should also investigate regeneration of spent biochar, nutrient recovery, removal of antibiotic-resistant bacteria, and integration with digital monitoring technologies. Combining BC-CWs with Internet of Things (IoT)-based sensors, artificial intelligence, and real-time water quality monitoring may further enhance treatment efficiency and operational management. Such smart wastewater treatment systems could play a significant role in future climate-resilient cities and sustainable aquaculture systems.

### Conclusion

Biochar-integrated constructed wetlands represent an innovative and environmentally sustainable solution for modern wastewater treatment challenges. By integrating the adsorption capacity of biochar with the ecological functions of constructed wetlands, this technology significantly enhances pollutant removal while remaining affordable, energy-efficient, and environmentally friendly. Beyond wastewater purification, BC-CWs promote carbon sequestration,

resource recovery, agricultural waste utilization, biodiversity conservation, and climate resilience. As nations increasingly pursue sustainable development pathways, biochar-integrated constructed wetlands provide a practical example of how scientific innovation can harness natural processes to address complex environmental challenges. Their ability to improve water quality, support circular economy principles, and contribute to climate action makes them a highly promising technology for achieving cleaner water, healthier ecosystems, and a more sustainable future. With continued research, policy support, and large-scale implementation, BC-CWs have the potential to become a cornerstone of decentralized wastewater management and an important contributor to the vision of Viksit Bharat 2047.

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# Synthetic Biology and Designer Microbes for Agriculture: An Emerging Revolution in Sustainable Farming

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Synthetic biology is transforming agriculture by enabling the development of designer microbes with enhanced abilities to support sustainable crop production. These engineered microorganisms can improve nutrient availability, promote plant growth, suppress diseases, enhance tolerance to drought and salinity, and reduce dependence on chemical fertilizers and pesticides. They also offer innovative applications in precision agriculture, biosensing, and bioremediation, contributing to improved soil health and environmental sustainability. Although challenges related to biosafety, regulation, ecological impacts, and public acceptance remain, continued advances in microbial engineering hold great promise for climate-smart farming. Designer microbes represent a revolutionary step toward resilient, productive, and sustainable agriculture.

## Introduction

As the world's population continues to grow and climate change places increasing pressure on agricultural systems, ensuring sustainable food production has become one of the greatest challenges. Conventional farming practices, which rely heavily on chemical fertilizers, pesticides and intensive resource use, have undoubtedly boosted crop yields but have also contributed to soil degradation, environmental pollution, biodiversity loss and greenhouse gas emissions. These challenges highlight the urgent need for innovative and environmentally friendly approaches that can improve agricultural productivity while preserving natural ecosystems.

One of the most promising advances in modern agricultural science is synthetic biology- an interdisciplinary field that combines biology, genetics, engineering and computational science to design organisms with new or enhanced functions. By precisely modifying the genetic makeup of beneficial microorganisms, scientists are creating designer microbes capable of performing targeted tasks in the agricultural ecosystem. Unlike conventional biofertilizers, these engineered microorganisms can be programmed to fix

atmospheric nitrogen more efficiently, solubilize phosphorus, enhance nutrient uptake, produce plant growth-promoting hormones, suppress plant pathogens, improve tolerance to drought and salinity and even detect environmental stress before visible symptoms appear.

The application of designer microbes represents a paradigm shift from chemical-dependent farming to biology-driven precision agriculture. These living microbial tools have the potential to reduce the excessive use of agrochemicals, improve soil fertility, increase crop resilience against climate stress, and support sustainable crop production with a lower environmental footprint. As research advances and regulatory frameworks evolve, synthetic biology is expected to play a pivotal role in developing the next generation of climate-smart agricultural technologies. This article explores how synthetic biology is transforming beneficial microorganisms into intelligent agricultural partners, examines their potential applications in sustainable farming, discusses current challenges and biosafety considerations, and highlights the future prospects of designer microbes in building a more productive, resilient and environmentally sustainable agricultural system.



## What is synthetic biology?

Synthetic biology is a new scientific field that combines biology, genetics, and engineering to create organisms with useful, customized functions. Instead of simply discovering what microbes naturally do, scientists can now redesign them to perform specific agricultural tasks such as supplying nutrients to crops, protecting roots from harmful pathogens, or helping plants withstand drought and other environmental stresses. Because of this ability to “program” beneficial microorganisms, synthetic biology is opening the door to a new generation of sustainable farming technologies.

## What are designer microbes?

Designer microbes are microorganisms (such as bacteria, fungi, algae or yeast) that have been intentionally modified or engineered to perform specific beneficial functions that they do not naturally perform or to perform natural functions more efficiently. These modifications are achieved using techniques from synthetic biology, genetic engineering or genome editing, allowing scientists to “program” microbes to solve real-world problems in agriculture, medicine, environmental protection and industry. Unlike naturally occurring beneficial microbes, designer microbes are used for a particular purpose. Scientists can add new genes, remove undesirable genes or alter existing genetic pathways so that the microorganisms produce desired compounds, respond to environmental signals or interact more effectively with plants and soil.

## Potential Applications of Designer Microbes in Agriculture

### 1. Biofertilizers for Enhanced Nutrient Use Efficiency

One of the most promising applications of designer microbes is improving nutrient availability to crops. Engineered bacteria can fix atmospheric nitrogen more efficiently, solubilize insoluble phosphorus,

mobilize potassium and produce siderophores that enhance iron uptake. These microbes reduce dependence on synthetic fertilizers while improving nutrient-use efficiency and crop yield.

#### Examples:

- Enhanced *Rhizobium* for biological nitrogen fixation
- Engineered *Azospirillum* and *Azotobacter* for improved nutrient delivery
- Modified *Bacillus* and *Pseudomonas* for phosphorus solubilization

### 2. Plant Growth Promotion

Designer microbes can be programmed to produce larger quantities of plant growth-promoting substances such as:

- Indole-3-acetic acid (IAA)
- Gibberellins
- Cytokinins
- ACC deaminase

These compounds stimulate root development, improve nutrient uptake, increase biomass production and enhance seed germination.

### 3. Biological Control of Plant Diseases

Beneficial microorganisms can be engineered to produce antimicrobial compounds, hydrolytic enzymes, bacteriocins and antifungal metabolites that suppress plant pathogens. They can also trigger induced systemic resistance (ISR), strengthening the plant's natural defense mechanisms.

#### Target pathogens include:

- *Fusarium*
- *Rhizoctonia*



- *Pythium*
- *Phytophthora*
- *Xanthomonas*

#### 4. Climate Stress Tolerance

Climate change exposes crops to drought, salinity, heat, and oxidative stress. Designer microbes can help plants tolerate these stresses by:

- Producing osmoprotectants
- Synthesizing exopolysaccharides (EPS)
- Enhancing antioxidant enzyme activity
- Regulating stress-responsive plant hormones
- Improving water retention around roots

This application is particularly valuable for climate-smart agriculture.

#### 5. Precision Agriculture Using Biosensors

Synthetic biology enables microbes to function as living biosensors capable of detecting:

- Nitrogen deficiency

- Phosphorus deficiency
- Soil pH changes
- Heavy metal contamination
- Pathogen invasion
- Water stress

Once a signal is detected, the engineered microbes can activate beneficial genes or produce molecules that help the plant respond to stress.

#### 6. Bioremediation of Agricultural Soils

Engineered microorganisms can remove or detoxify contaminants such as:

- Pesticide residues
- Herbicides
- Petroleum hydrocarbons
- Heavy metals
- Excess nitrates

This application restores polluted agricultural land while protecting groundwater and ecosystems.

**Table 1 Major agricultural applications of designer microbes**

| Agricultural challenge       | Designer microbe strategy                                | Benefit to crops and environment          |
|------------------------------|----------------------------------------------------------|-------------------------------------------|
| Nitrogen deficiency          | Enhanced biological nitrogen fixation                    | Reduced nitrogen fertilizer requirement   |
| Poor phosphorus availability | Phosphate-solubilizing microbes                          | Improved phosphorus uptake                |
| Soil nutrient imbalance      | Potassium-mobilizing bacteria and siderophore production | Enhanced nutrient use efficiency          |
| Plant diseases               | Production of antimicrobial compounds and ISR activation | Reduced dependence on chemical pesticides |
| Drought stress               | EPS-producing and Osmo protectant-                       | Improved water retention and drought      |



|                   |                                                           |                                                |
|-------------------|-----------------------------------------------------------|------------------------------------------------|
|                   | producing microbes                                        | tolerance                                      |
| Salinity stress   | Regulation of stress-responsive metabolites               | Increased salt tolerance                       |
| Poor root growth  | Increased production of IAA, gibberellins and cytokinins  | Better root development and higher biomass     |
| Soil pollution    | Engineered microbes for biodegradation and detoxification | Restoration of contaminated agricultural soils |
| Climate change    | Carbon-fixing and carbon-sequestering microbes            | Reduced greenhouse gas emissions               |
| Precision farming | Microbial biosensors for nutrient and pathogen detection  | Efficient and targeted crop management         |

## Challenges and concerns

Despite their immense potential, there are significant scientific, regulatory, environmental and societal hurdles to widespread use of designer microorganisms in agriculture. One of the key issues is biosafety since genetically engineered microbes discharged into the environment could interact with native microbial communities, convey designed genes to other organisms through horizontal gene transfer or have unforeseen ecological effects. However, it is technically tough to ensure the long-term survival, stability and predictable performance of designer microbes in a range of field circumstances as their effectiveness can be influenced by environmental factors such as soil type, temperature and microbial competition. Furthermore, rigorous governmental approval procedures, expensive research and development and the general public's low acceptance of genetically modified organisms (GMOs) and ethical concerns about the deliberate release of modified germs may impede commercialization. Therefore, it is vital to make extensive risk assessments, implement rigorous biosafety measures, build transparent legislation, and promote effective public involvement to guarantee designer microorganisms are created and deployed in

a safe, responsible and sustainable manner for the benefit of agriculture and the environment.

## Conclusion

Synthetic biology and designer microbes are redefining the future of agriculture by offering innovative, sustainable, and environmentally friendly solutions to some of the most pressing challenges facing global food production. By engineering beneficial microorganisms with enhanced capabilities, scientists are developing next-generation biofertilizers, biopesticides, and plant growth-promoting agents that can improve nutrient use efficiency, enhance crop resilience to climate stress, restore soil health, and reduce dependence on chemical inputs. Although challenges related to biosafety, regulatory approval, ecological impacts, and public acceptance must be carefully addressed, continued advances in synthetic biology, genome editing, and microbial engineering are accelerating the development of safe and effective microbial technologies. With responsible innovation, rigorous risk assessment and supportive policies, designer microbes have the potential to become key components of climate-smart and precision agriculture, paving the way toward a more





productive, resilient, and sustainable farming system that can help ensure global food security for future generations.

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# Nutritional and Medicinal Significance of Sapota

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Sapota (*Manilkara zapota* L.), alternatively referred to as sapodilla or chikoo, is a significant tropical and subtropical fruit crop due to its tasty nature, nutrient content and medicinal values. It is an evergreen fruit tree from the family Sapotaceae and has been cultivated extensively in India and other tropical zones. The fruit contains a sweet, granular, aromatic and tasty pulp that is consumed fresh or can be processed into shakes, jam, desserts, beverages, ice cream, and fruit leather. In addition to the dietary value, different parts of the sapota plant including fruits, leaves, seeds, bark and latex have been used in ethnomedicine.

Various studies have demonstrated the numerous biological activities exhibited by the sapota including antioxidants, anti-inflammatory, antimicrobial, antidiarrheal, antihyperglycemic, antidiabetic, analgesic, wound healing, spasmolytic and expectorant activities. All these activities are due to the presence of biologically active components like tannins, polyphenols, flavonoids, phenolic compounds, saponins, alkaloids, glycosides, latex contents, vitamins and minerals in the plant parts.

Sapota is another rich source of energy and nutrients. It provides carbohydrates, fiber, vitamins, and minerals that help improve the functioning of the digestive system, the immune system, and cardiovascular system. Dietary fiber helps in the process of digestion, while potassium plays a role in maintaining normal blood pressure and healthy muscles. Vitamin A and vitamin C, as well as phenols and other antioxidants, protect the body from oxidation.

The plant has different common names depending on the region of the world. For example, it is called chikoo in Hindi, rata sapotta in Tamil, chikkoo in Malayalam, sapota in Telugu, sapeda in Bengali, sapote in Spanish, sapotilha in Portuguese, sapotillier in French, and sapodilla and naseberry in English. The importance of sapota as a fruit crop for people's health and well-being cannot be underestimated.

## Morphology

Sapota is a moderate-sized, long-lived evergreen tree capable of attaining a height of about 10-20 metres

under favorable circumstances. It grows a straight, strong stem, which may be 50 cm wide at the base. The crown is usually dense, thick and broad or pyramidal. Sapota trees provide significant shades due to its thick canopy. The bark is thick, brown-grey and fissured. Injuries on the plant release a white sticky substance known as latex.

The branches of young trees are usually hairless and brownish colored. Twigs are strong and cylindrical and bear leaves at their tip ends. Leaves are simple, alternate and leathery. They are elliptical to oblong lanceolate and grow up to 5-15 cm in length and 3-6 cm in width. Their upper side is glossy while the lower part is pale. They come to an abrupt termination, with acuminate to obtuse tips. Petioles are short, growing up to 0.5-2 cm. Lateral veins curve towards the margins of the leaves.

The fruit takes the form of a round to oblong berry that usually attains a length of 5–10 cm and weighs around 100–400 grams, depending on cultivar and growth conditions. The skin is tough, leathery and scaly in appearance. The flesh is soft and



granular with a sweet taste and is colored white to brown when ripe. The flesh is filled with latex canals and has a distinctive flavor. The inner section of the fruit contains oblong black seeds that are glossy in appearance. Normally, the seeds have a length of about 3–4 cm, but different cultivars may vary with respect to the number of seeds.

### Medicinal Significance

The sapota tree has been known to be of medicinal importance due to its various parts which have been found to have many therapeutic uses. The fruits are eaten as food by people while the leaves, bark and seeds have been used traditionally in different combinations for treatment of various ailments.

The fruit has high amount of carbohydrates and dietary fiber and hence can provide energy along with aiding digestion. The dietary fiber helps promote bowel movements and could prevent constipation. Potassium present in the fruit is necessary for regulating body fluids, nerve and heart functions. The vitamins A and C are essential for the immune system and for skin health.

Phytochemicals are thought to be the main reason why sapota has medicinal use. Tannins are astringent substances that can help reduce diarrhea and heal wounds. Polyphenols and flavonoids have antioxidant and anti-inflammatory capabilities. Saponins, alkaloids and other secondary metabolites are said to be effective against microbes, metabolism and protection.

Leaves of sapota are known to be analgesics, antibacterial agents, spasmolytics and expectorants. Traditional use of leaf preparations was to relieve respiratory problems, toothaches, irritated skin and ulcers. Bark and latex of sapota have been used due to astringency and protective capabilities.

### Medicinal importance of different plant parts

| Parts of Plant | Compound                                        | Effect                                                                                 |
|----------------|-------------------------------------------------|----------------------------------------------------------------------------------------|
| Bark           | Tannins, latex                                  | Anti-inflammatory, wound healing; strong astringent for skin ailments                  |
| Seed           | Saponins, sapotin, sapotanine, phenols          | Antidiarrheal, antioxidant; improves vision and bone strength                          |
| Pulp/Fruit     | Polyphenols, vitamins A & C, fiber, carotenoids | Antineoplastic, immune-boosting, digestive aid; antihyperglycemic                      |
| Leaves         | Flavonoids, alkaloids, tannins                  | Antioxidant, antimicrobial, analgesic, anti-diabetic; hepatoprotective and expectorant |

### Nutritional Profile

Sapota is a nutritionally dense tropical fruit, containing carbohydrates, dietary fiber, vitamins, minerals and other biologically active substances. 100 g of fresh sapota pulp provides 83 kcal of energy and about 20 g of carbohydrates. Carbohydrates are mainly in the form of natural sugars, contributing to the sweet taste of the fruit.

Dietary fiber is contained in the fruit and helps maintain regularity of digestion. It may improve motility and prevent constipation. Sapota also contains little amounts of proteins and fats.

Among the key microelements contained in sapota are vitamin C, vitamin A, potassium, calcium, phosphorus and iron. Vitamin C helps to support the body's immune function and acts as an antioxidant.



Vitamin A is required for good vision, healthy functioning of the epithelium and normal immunity. Potassium is necessary to maintain water balance, transmit nerve impulses and ensure proper muscle work.

### Nutritional value per 100gm edible portion

| Nutrients     | Quantity(per 100gm) |
|---------------|---------------------|
| Energy        | 83 Kcal             |
| Carbohydrates | 19.9 gm             |
| Protein       | 0.44 gm             |
| Total Fat     | 1.10 gm             |
| Vitamin A     | 60 IU               |
| Vitamin C     | 14.7 mg             |
| Potassium     | 193 mg              |
| Calcium       | 21 mg               |
| Phosphorus    | 12 mg               |

The presence of carbohydrates, fiber, vitamins and minerals makes sapota an essential ingredient in a nutritious diet. Due to its sweetness and high energy value, sapota is highly valuable as a fresh fruit and a food ingredient in processed foods. It could also contribute to the diversification of diets in tropical countries where fruits are grown.

### Phytochemical Profile

In sapota, there is a broad spectrum of phytochemicals existing in different plant parts. These phytochemicals include polyphenols, tannins, flavonoids, phenolic, carotenoids, and other antioxidants found in the fruit. There are flavonoids, alkaloids, and tannins in the leaves, whereas saponins are present in the seeds.

All these phytochemicals play a significant role because they might have different biological mechanisms of action. Polyphenols and flavonoids can scavenge the reactive oxygen species, while tannins may act astringently and as antimicrobials. On the one hand, saponins may interact with cell membranes and serve for biological defense.

### Anticancer/Antitumor Activity

There is evidence suggesting that oxidative stress and an increase in the production of reactive oxygen species are potential causes of cellular injury and various chronic illnesses. The presence of antioxidants such as phenols and flavonoids in Sapota can potentially prevent reactive oxygen species and protect cells from any harm.

Experiments conducted with extracts of different plants have suggested that certain bioactive substances found in sapota have the capacity to affect the processes involved in the formation of tumor cells and the process of programmed cell death. The polyphenolic compounds in Sapota can help protect the cellular components against oxidative damage and also affect the processes involved in cell proliferation.

### Antidiabetic and Anti-Hyperglycemic Activity

Diabetes mellitus is defined as a metabolic condition characterized by high blood sugar due to insufficient insulin production or reduced insulin activity, or even both. Studies on medicinal plants revealed that the fruit and leaves extracts of sapota might have some anti-hyperglycemic effects.

Some of the polyphenolic and non-polyphenolic phytochemicals may affect the metabolism of carbohydrates by inhibiting digestive enzymes like  $\alpha$ -amylase and  $\alpha$ -glucosidase that break down complex carbohydrates. This effect could help reduce the quick release and absorption of glucose post meal consumption. Further studies could demonstrate the



impact of sapota on glucose transport, insulin sensitivity, and pancreas functioning.

### **Antioxidant Activity**

Oxidative stress is defined by the formation of more amounts of reactive oxygen species than the normal capability of the organism to produce antioxidants for protection against them. Oxidative stress, in excess amounts, could be harmful, causing damage to lipids, proteins, DNA and could lead to the development of aging and chronic diseases.

Sapota is a source of phenols, flavonoids, tannins, vitamin C and other types of antioxidants which can protect against the formation of free radicals. The extracts of various plant parts of sapota have been found to have antioxidant activities in in-vitro tests such as the DPPH and ABTS radical scavenging test.

### **Antidiarrheal Activity**

Sapota is traditionally known to be used for treating diarrhoea. Tannins are believed to play a major role in this case due to their astringent nature, and hence, could act to decrease excess secretion of the gut and also affect the motility of the gastro-intestinal system.

In experimental studies, extracts from the plant have been shown to exhibit antidiarrheal activities. However, in cases of extreme diarrhoea, medical treatment should be sought as it can lead to dehydration and electrolyte imbalance.

### **Antimicrobial Activity**

Sapota has various substances that could show antimicrobial properties towards selective microorganisms. Studies on leaf extract, seed extract, bark extract and latex extract have been conducted for their effect against different types of bacteria and fungi.

Flavonoids, tannins, saponins and other phytochemicals could affect the microbial cell walls and cell membrane and inhibit the activities of the

microbes. Laboratory researches have shown antimicrobial properties towards specific Gram-positive and Gram-negative bacteria, as well as some fungi.

The antimicrobial properties of sapota could be used in the formulation of natural preservatives and herbal preparations. More studies are required to determine the effective concentration levels and applications.

### **Anti-inflammatory and Analgesic Properties**

Inflammation is the natural defense mechanism of the body; however, inflammation, especially if it persists for a long period of time, can lead to chronic diseases. Flavonoids and phenolics found in sapota may have anti-inflammatory properties due to their effect on oxidative and inflammatory systems.

Leaves of the sapota tree have been used for the treatment of conditions related to pain and inflammation. There have been laboratory studies suggesting analgesic effects in some plant extracts.

### **Conclusion**

Sapota (*Manilkara zapota* L.) is an important tropical fruit crop with great nutritional, medicinal and economical significance. Its fruit is a source of energy, dietary fiber, vitamins and essential minerals like potassium, calcium, phosphorus and vitamin C which are responsible for digestive health, immune function, cardiac well being and general nutritional health.

Apart from the nutritional benefits, the sapota fruit possesses a wide array of bioactive compounds such as tannins, polyphenols, flavonoids, phenolic compounds, saponins and alkaloids. These compounds are known to possess antioxidant, antimicrobial, anti-inflammatory, antidiarrheal, analgesic, antidiabetic and antihyperglycemic properties. The various parts of the plant, namely fruit, leaves, seeds, bark and latex have been





exploited for their medicinal applications and are attracting scientific attention.

The nutritional profile and phytochemistry of the sapota fruit makes it a valuable fruit for the development of functional foods and natural products. The possible use of the fruit to combat oxidative stress, digestive health and metabolic well being further adds to the significance of the fruit.

Nevertheless, most of the medicinal benefits are yet to be scientifically substantiated through appropriate experiments and clinical trials.

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# Interiorscaping: Bringing Nature Indoors for a Healthier and Happier Life

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In today's fast-moving urban world, people spend most of their time inside homes, offices, malls, classrooms and commercial buildings. While cities continue to grow vertically with concrete structures and glass buildings, our connection with nature is slowly fading. Busy schedules, limited outdoor spaces and increasing pollution have made modern lifestyles stressful and unhealthy. As a result, people are now looking for ways to reconnect with greenery and create calm, refreshing living spaces indoors.

This growing need has given rise to a beautiful and meaningful concept known as interiorscaping. More than just decorating rooms with plants, interiorscaping creates a harmonious relationship between humans and greenery. Indoor plants not only beautify interiors but also improve air quality, reduce stress and enhance emotional well-being. Today, interiorscaping has become an essential part of modern interior design, sustainable living and healthy lifestyles.

## Interiorscaping

Interiorscaping refers to the practice of growing, arranging and maintaining plants inside buildings for functional, aesthetic and environmental purposes. It combines horticulture with interior design to create visually pleasing and healthier indoor environments. Interiorscaping is considered one of the least expensive and most natural ways to purify indoor air and maintain a fresh atmosphere.

Unlike traditional gardening, interiorscaping focuses on enclosed spaces such as living rooms, offices, hotels, hospitals, restaurants and shopping complexes. It involves careful selection of plants according to light, humidity, temperature and available space. Whether it is a small terrarium on a study table or a large vertical garden in a corporate office, interiorscaping transforms dull spaces into vibrant and lively environments.

## Why Indoor Greenery Matters Today

Modern urban life has increased our dependence on artificial environments. Air conditioners, electronic devices, synthetic furniture, paints and cleaning chemicals release harmful pollutants indoors. Surprisingly, indoor air can sometimes be more polluted than outdoor air. Volatile organic compounds (VOCs), carbon dioxide, particulate matter and formaldehyde commonly accumulate inside buildings and negatively affect human health.

Indoor plants act as natural air purifiers by absorbing pollutants and releasing oxygen. Research has shown that plants such as spider plant, peace lily, snake plant, pothos and aloe vera help reduce indoor toxins and improve air quality. Their presence also increases humidity, making indoor spaces more comfortable, especially in air-conditioned environments.

However, the importance of interiorscaping goes beyond environmental benefits. In recent years, people have started realizing the emotional and



psychological healing power of plants. After the COVID-19 pandemic, indoor gardening and green interiors became more popular because people wanted peaceful, refreshing and mentally comforting surroundings.

### Nature's Therapy: Mental Health and Emotional Wellness

One of the most fascinating aspects of interiorscaping is its positive effect on human psychology. Scientific studies and practical experiences both suggest that indoor plants reduce anxiety, stress and mental fatigue. Green spaces create feelings of calmness, relaxation and positivity.

In offices, indoor plants improve concentration, creativity, and productivity. Employees working in green surroundings often feel more motivated and emotionally balanced. In hospitals and healthcare spaces, plants create soothing environments that support recovery and emotional healing. The therapeutic role of gardening, often called *horticultural therapy*, is now being widely recognized for improving mental health and emotional well-being.

Even a small green corner in a home can make a huge difference. Watching plants grow, watering them daily and caring for them creates a sense of connection with nature that many urban residents deeply miss.

### Popular Indoor Plants and Their Benefits

Different indoor plants serve different purposes in interiorscaping. Some are known for air purification, while others are valued for their decorative appeal or calming effect.

#### 1. Snake Plant (Sansevieria)

**Scientific name:** *Sansevieria trifasciata*  
**Family:** Asparagaceae

Regarded as one of the best beginner-friendly indoor plants, the snake plant is famous for its hardiness and air-purifying ability. Its upright sword-shaped leaves with attractive green and yellow variegation make it a stylish addition to modern interiors. One of its unique qualities is that it releases oxygen even during the night, making it highly suitable for bedrooms and study rooms. The plant is known to absorb harmful indoor pollutants such as formaldehyde, benzene and xylene, thereby improving indoor air quality. Snake plants require very little maintenance, tolerate low light conditions and survive with minimal watering, making them ideal for busy urban lifestyles.



#### 2. Peace Lily

**Scientific name:** *Spathiphyllum wallisii*  
**Family:** Araceae

Peace lilies are elegant indoor plants admired for their glossy dark green foliage and graceful white flowers. They are widely used in interiorscaping because of their sophisticated appearance and excellent air-purifying qualities. Peace lilies help remove indoor pollutants like ammonia, benzene and formaldehyde from the air while increasing indoor humidity levels. Their calming appearance creates a soothing atmosphere in homes, offices, and hospitals. These plants thrive well in indirect light and require moderate watering, making them suitable for indoor decorative arrangements. Beyond aesthetics, peace lilies are often associated with peace, positivity and emotional comfort.





### 3. Spider Plant

**Scientific name:** *Chlorophytum comosum*  
**Family:** Asparagaceae

Spider plants are among the most adaptable and easy-to-grow indoor plants. Their arching green leaves with white stripes create a fresh and lively appearance that brightens indoor corners beautifully. Spider plants are excellent natural air cleaners and are especially effective in reducing carbon monoxide, formaldehyde and other indoor toxins. They are highly recommended for homes and offices because they improve indoor air quality while requiring minimal care. Spider plants also produce small plantlets which add ornamental value and can easily be propagated into new plants. Their resilience and attractive foliage make them a favourite choice for hanging baskets and shelves.



### 4. Pothos (Money Plant)

**Scientific name:** *Epipremnum aureum*  
**Family:** Araceae

Pothos, commonly known as money plant, is one of the most popular indoor plants in Indian households. It is valued for its attractive trailing vines and heart-shaped leaves that create lush green aesthetics in interiors. This versatile plant can grow both in water and soil, making it highly convenient for indoor decoration. Pothos is known for its ability to absorb indoor pollutants and improve air quality naturally. It grows rapidly and looks beautiful when placed in hanging baskets, shelves, window areas or vertical gardens. Due to its low maintenance requirements and symbolic association with prosperity and good luck, the money plant remains a favourite choice for homes and workplaces.



### 5. Aloe vera

**Scientific name:** *Aloe barbadensis*

**Family:** Liliaceae

Aloe vera is a highly valued medicinal and ornamental indoor plant known for its thick succulent leaves filled with soothing gel. Apart from its traditional medicinal uses in skincare and wound healing, aloe vera also helps improve indoor air quality by absorbing harmful chemicals present in household products. Its compact and modern appearance makes it ideal for contemporary interiors. Aloe vera requires very little maintenance, thrives in bright indirect sunlight and needs minimal watering due to its drought-tolerant nature. Because of its health benefits and decorative appeal, it is widely grown in kitchens, balconies and living spaces.







## 6. Areca Palm

**Scientific name:** *Dypsis lutescens*  
**Family:** Arecaceae

Areca palm is a graceful tropical plant widely used in interiorscaping for its feathery green fronds and elegant appearance. It instantly adds freshness, softness and a luxurious tropical feel to indoor spaces. Besides enhancing aesthetics, areca palm acts as a natural humidifier by releasing moisture into the air, which helps maintain indoor humidity and comfort. It is also effective in filtering airborne toxins and improving indoor air quality. This plant performs best in bright indirect light and requires regular watering for healthy growth. Due to its lush foliage and refreshing appearance, areca palm is commonly placed in hotel lobbies, offices, living rooms and spacious interiors.



## Creative Ways of Interiorscaping

Interiorscaping offers endless creative possibilities. Even small spaces can be transformed beautifully through smart plant arrangements.

### 1. Hanging Baskets

Hanging baskets are versatile decorative containers, with endless variations and customizable designs. They are perfect for balconies and compact interiors where floor space is limited.



### 2. Miniature Gardens

Miniature gardens recreate natural landscapes in small containers using dwarf plants, stones, and decorative accessories. They require shallow yet well drained soil layers and foster creativity and aesthetic expression. Ideal for tabletops or desks, they bring nature to confined interiors.





### 3. Room Dividers

Plants act as natural partitions in large rooms, subtly separating functional zones while preserving openness. Instead of dense plant walls, strategic placement of a few tall or grouped plants often enhances spatial flow. They also supply greenery without compromising light.



### 4. Window Gardening

Windows provide ideal lighting conditions for indoor plants. Properly arranged plants around windows create beautiful framing effects and maximize sunlight use. Plant shapes should complement the window style, creating harmonious framing effects. North-facing windows suit shade lovers; sunny exposures support light-demanding flora.



### 5. Terrariums

Terrariums are sealed glass environments that maintain humidity and support delicate tropical species. They create self-sustaining microclimates through moisture recycling and are excellent for propagation and display. Proper plant selection ensures balance and long-term health.



### 6. Bottle Gardens

Bottle gardens are enclosed plant environments, ideal for small decorative spaces and humid-loving species. Inspired by Wardian cases, they create self-contained ecosystems requiring minimal maintenance. Their transparency enhances visual appeal and botanical appreciation.



## 7. Vertical Gardens

Vertical gardens utilize vertical structures walls, railings and panels to cultivate plants in compact urban environments. They maximize space efficiency, enhance aesthetics and improve air quality. Hanging pots and modular units make them suitable for balconies and apartments.



## 8. Garden Rooms

Garden rooms are plant-focused extensions of living spaces, providing light, comfort and humidity for thriving greenery. Equipped with tiled floors, water access and relaxed furnishings, they mimic small conservatories. Their purpose is to blend leisure with horticultural enjoyment.



## 9. Brightening Small Areas

Compact spaces benefit from small, brightly colored or texturally rich plants that animate dull interior corners. Tall and small specimens may be combined

to create contrast and visual hierarchy. Well-chosen species deliver ornamentation without overcrowding.



## 10. Contrasting Shapes

The different shapes of indoor plants are most successfully accentuated when one shape is placed in striking just a position with an obvious opposite. Upright shapes associate with low rosettes, climbers with trailers.



## Sustainability and Eco-Friendly Living

Interiorscaping also supports sustainable living. Green interiors help regulate indoor temperature naturally, reducing excessive dependence on cooling systems. Plants absorb carbon dioxide, increase humidity and create healthier microclimates indoors.

Today, eco-friendly interior design encourages the use of recyclable containers, organic materials, sustainable decor elements and water-efficient gardening methods. Green homes are not only visually pleasing but also environmentally responsible.





## Interiorscaping in Everyday Life

The beauty of interiorscaping lies in its simplicity and accessibility. One does not need a large garden or expensive setup to experience its benefits. A small succulent on a study table, a peace lily in the living room, or a vertical garden on a balcony can completely change the atmosphere of a space.

Many cafes now use plant-filled interiors to create relaxing customer experiences. Offices use greenery to reduce workplace stress. Hospitals incorporate healing gardens to improve patient recovery. Even schools and libraries are adopting green interiors to encourage better concentration and calmness.

Interiorscaping is no longer just a decorative luxury—it has become a necessity for healthier urban living.

## Conclusion

As urbanization continues to dominate modern life, the importance of reconnecting with nature becomes

even more significant. Interiorscaping offers a simple yet powerful solution by bringing greenery into our everyday environments. It transforms indoor spaces into healthier, calmer, and more aesthetically pleasing places while improving physical health, emotional well-being, and environmental quality.

From vertical gardens, terrariums and smart green homes, interiorscaping represents the future of sustainable and mindful living. In a world filled with screens, stress and concrete structures, indoor plants quietly remind us of nature's healing presence.

Ultimately, interiorscaping is not just about decorating interiors—it is about creating spaces where people can breathe better, think better, feel happier and live more peacefully with nature around them.

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# Botanical Pesticides: A Key Driver for Sustainable and Natural Farming in India

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Indian agriculture's heavy dependence on synthetic pesticides has triggered severe environmental degradation, widespread pest resistance, and escalating human health risks, including pesticide residues in food chains (War *et al.*, 2014). Botanical pesticides—derived from plant-based bioactive compounds—offer eco-friendly alternatives that align seamlessly with sustainable and natural farming paradigms (Dougoud *et al.*, 2019). This comprehensive review synthesizes evidence from peer-reviewed studies (2014–2025), demonstrating that neem (*Azadirachta indica*) extracts achieve 30–96% larval reduction against *Helicoverpa armigera* in field trials, alongside potent insecticidal, antifeedant, growth-regulating, and repellent effects on key pests like whiteflies (*Bemisia tabaci*), aphids (*Aphis craccivora*), and brinjal shoot and fruit borers (*Leucinodes orbonalis*) (Agale *et al.*, 2019;). Additional botanicals such as *Derris indica* (rotenone), *Vitex negundo*, and *Adhatoda vasica* exhibit synergistic potential under Indian agro-climatic conditions (Devi *et al.*, 2024;). These pesticides provide biodegradability (degrading within 3–7 days), minimal toxicity to non-target organisms (e.g., pollinators, predators), and excellent compatibility with Integrated Pest Management (IPM) systems (Khanal *et al.*, 2025). Aligned with national initiatives like the National Mission on Natural Farming (NMNF, approved 2024 with ₹2,481 crore targeting 1 crore farmers) and Paramparagat Krishi Vikas Yojana (PKVY), they reduce chemical inputs by 40–60% while cutting costs for smallholders. However, challenges including field efficacy variability, short persistence, formulation instability, and limited commercialization hinder scalability. Strategic interventions—nano-emulsions, standardized extracts, policy incentives via the Draft Pesticides Management Bill 2025, and extension services—can propel adoption, fostering resilient, zero-budget natural farming across India's diverse cropping systems.

## Introduction

India, the global agricultural powerhouse feeding 1.4 billion people, grapples with the fallout of Green Revolution-era chemical intensification (War *et al.*, 2014). Annual synthetic pesticide consumption exceeds 60,000 metric tons, leading to soil salinization, water eutrophication, biodiversity loss, and pest resurgence—*H. armigera* resistance to organophosphates now exceeds 70% in cotton belts. Residue violations in exports (e.g., chili, okra) cost farmers millions, while farmworker poisonings claim over 10,000 lives yearly (Dougoud *et al.*, 2019). This crisis demands a paradigm shift toward sustainable alternatives.

Botanical pesticides revive indigenous wisdom—neem twigs as pest brushes in Vedic texts—now validated by modern science (Devi *et al.*, 2024). They embody the United Nations Sustainable Development Goal 2 (Zero Hunger) and India's NMNF, a ₹2,481 crore mission launched in late 2024 targeting 1 crore farmers across 15,000 clusters by 2026, promoting Jeevamrutha-based natural farming with zero-chemical protocols. Complementing PKVY's ₹31,000/ha organic cluster subsidies (covering 7.25 lakh ha as of 2025), botanicals enable chemical-free transitions in rice-wheat, pulses, horticulture, and cotton belts. Their multi-mode action—unlike synthetics' single-site targets—curbs resistance, as *H. armigera* shows <5% cross-



resistance to azadirachtin. Recent adoption in Andhra Pradesh (5.8 lakh farmers under NMNF pilot) yields 10–20% higher net returns via reduced inputs. This review dissects their mechanisms, efficacy against major pests, integration into natural farming, advantages/limitations, and scale-up pathways, positioning botanicals as linchpins for resilient Indian agriculture amid climate volatility and the Pesticides Management Bill 2025's biopesticide push.

### Botanical Pesticides: Concept and Mechanisms of Action

Botanical pesticides encompass secondary metabolites from >2,000 plant species: alkaloids (nicotine from tobacco, rauwolfia), terpenoids (limonene from citrus, eugenol from clove), phenolics (tannins from acacia, flavonoids from tulsi), and steroids (withaferin A from ashwagandha) (Dougoud *et al.*, 2019). Extracted via cold aqueous infusion, ethanol maceration, or supercritical CO<sub>2</sub> from seeds (*neem*, *karanja*), leaves (*tulsi*, *mint*, *lantana*), bark (*cinnamon*, *neem*), or roots (*sweet flag*, *derris*), they deploy diverse modes of action:

- **Neurotoxicity:** Pyrethrins from *Tagetes erecta* or *Chrysanthemum* prolong sodium channel opening, causing paralysis (LD50 0.5–2 µg/insect) (War *et al.*, 2014).
- **Respiratory/Mitochondrial inhibition:** Rotenone from *Derris indica* blocks Complex I electron transport.
- **Hormonal disruption:** Azadirachtin mimics ecdysone antagonists, blocking molting and reproduction; phytoecdysones from *Ajuga* induce premature molts (Khanal *et al.*, 2025).
- **Antifeedants/Repellents/Deterrents:** Capsaicin (*Capsicum*), quercetin (*onion*), and essential oils mask host kairomones, slashing feeding by 70–90% within 24h (Devi *et al.*, 2024).

Neem's >300 limonoids, spearheaded by azadirachtin (0.2–0.4% in seeds), exemplify synergy: azadirachtin halts juvenile hormone biosynthesis in corpora allata; salannin and nimbin suppress gustatory stimulants; meliantriol enhances cuticular penetration. This multi-targeting yields resistance incidence <1% versus 50% for pyrethroids (Dougoud *et al.*, 2019). Formulation advances—nano-capsules (100–500 nm entrapment) and emulsifiable concentrates (EC)—boost photostability 5-fold, extending field persistence from 3 to 14 days under India's high UV/humidity. Unlike persistent organochlorines (DT50 >100 days), botanicals fully mineralize within weeks, averting bioaccumulation in food webs (War *et al.*, 2014).

### Efficacy Against Major Insect Pests in Indian Conditions

Extensive field trials across India affirm botanicals' efficacy against polyphagous lepidopterans, hemipterans, and coleopterans. Neem Seed Kernel Extract (NSKE 5%) reduces *H. armigera* (Hub.) larvae by 71% after three sprays in pigeonpea, outperforming spinosad (65%) and correlating with 52% pod damage reduction (Agale *et al.*, 2019). Azadirachtin 0.3–1% EC (e.g., Neemarin) achieves 96% mortality at 7 days after treatment (DAT) in tomato, nearing chlorpyrifos yet residue-free. In cotton IPM, neem oil 1% + *Ha* NPV synergizes 85% control (vs. 62% NPV alone); pod borer (*H. armigera*) in pulses drops 78% with *Derris* 2% rotenone. Whitefly (*B. tabaci*) populations on brinjal plummet 60–80% via *Lantana camara* leaf + neem (LC50 1.2%); aphids (*A. craccivora*) on mustard succumb to *Azadirachta* + garlic clove extract (82% at 5 DAT) (Devi *et al.*, 2024). Brinjal fruit and shoot borer (*L. orbonalis*) damage halves (52% vs. 28% check) with *Vitex negundo* 1% emulsions.

Optimal protocols: Initiate at economic thresholds (ET: 5–8 larvae/plant for *H. armigera*), repeat at 10–15 days intervals (3–4 sprays/season). Synergists like Tween-80 (0.1%) enhance leaf wetting; UV





protectants (piperonyl butoxide) counter with highest B:C ratios in pulses/horticulture (Agale photodegradation, sustaining efficacy >70% even *et al.*, 2019).  
post-rain. Return on investment (ROI) hits 1:3.2–4.5,

**Table 1: Field Efficacy of Select Botanicals (India, 2018–2025)**

| Plant/Source            | Active Compound(s)    | Target Pest/Crop              | % Reduction / Mortality (DAT) | Superior to Comparator |
|-------------------------|-----------------------|-------------------------------|-------------------------------|------------------------|
| NSKE 5%                 | Azadirachtin + nimbin | <i>H. armigera</i> /Pigeonpea | 71% larvae (14)               | Spinosad (65%)         |
| Azadirachtin 0.3% EC    | Azadirachtin          | <i>H. armigera</i> /Tomato    | 96% (7)                       | Chlorpyrifos (92%)     |
| <i>Derris indica</i> 2% | Rotenone              | Aphids/Mustard                | 82% (5)                       | Imidacloprid (88%)     |
| <i>Lantana</i> + Neem   | Phenolics + limonoids | Whitefly/Brinjal              | 78% (10)                      | Untreated              |
| <i>Vitex negundo</i> 1% | Negundoside           | Fruit borer/Brinjal           | 52% damage cut                | Check (28%)            |

### Promoting Natural Farming in India

- ❖ **Environmental Sustainability:** With half-lives of 1–3 days, botanicals spare edaphic microbiota, earthworms (LC50 >10,000 ppm vs. 50 for carbofuran), and natural enemies—*Trichogramma chilonis* parasitism rises 15–20% post-neem (Dougoud *et al.*, 2019). NMNF's microbial Jeevamrutha (cow dung + botanicals) enhances soil C: N by 25%, curbing emissions.
- ❖ **Reduction in Chemical Dependency:** PKVY's 10 lakh ha organic clusters (2025) slash synthetics 50–70%, dodging ₹5,000/ha residue rejections; 40% farmers report pest equilibrium post-adoption.

- ❖ **Economic Viability for Smallholders:** On-farm NSKE (₹10–20/L) vs. synthetics (₹250–400/L) saves 25–40%; Andhra NMNF paddy nets ₹1.5 lakh/ha (vs. ₹1.2 lakh chemical). Botanical market CAGR 11.5% (India share 12%) hits USD 1B by 2030.
- ❖ **Seamless IPM Compatibility:** Vertical integration: Pheromone traps (Week 1), NPV/Bt (Day 3), neem booster (Day 7), cultural refusals. Pesticides Management Bill 2025 expedites biopesticide nods (6 months vs. 24), subsidizing 50% R&D.



**Table 2: Policy Support Metrics for Botanicals**

| Initiative           | Budget/Target (2026)     | Botanical Provisions  | Projected Impact       |
|----------------------|--------------------------|-----------------------|------------------------|
| NMNF                 | ₹2,481 Cr / 1 Cr farmers | Neem seed hubs, demos | 20% input cut; 1 Cr ha |
| PKVY                 | ₹31k/ha / 10L ha         | Organic IPM kits      | ₹20–30k/ha savings     |
| Pesticides Bill 2025 | Regulatory reform        | Fast-track bio-reg    | 30% market shift       |

## Advantages and Limitations

### Key Advantages:

- Eco-profile: Degrades 90% in 72h; zero MRL violations (War *et al.*, 2014).
- Safety: Mammalian LD50 >5,000 mg/kg; bee LD50 >100 µg/bee (Dougoud *et al.*, 2019).
- Resistance-proof: <1% incidence via cocktails (Khanal *et al.*, 2025).
- Accessibility: Farmer-formulated (ROI 1:4).

### Principal Limitations:

- Variability: Active content fluctuates 0.01–1.5% (season/clone) (Devi *et al.*, 2024).
- Persistence: 3–5 days (rainfall halves efficacy 30%).
- Scale: <10% adoption; poor shelf-life (6 months).
- Awareness: Extension reaches <20% smallholders (Khanal *et al.*, 2025).

Solutions: GC-MS standardization (PUSA Gold: 0.15% azadirachtin fixed); polymer nano-liposomes (persistence x3).

## Future Prospects

Emerging nano-botanicals—azadirachtin chitosan nanoparticles (90% controlled release, 95% efficacy)—and RNAi-phytolures target novel pathways (Khanal *et al.*, 2025). AI apps (e.g., Kisan Suvidha pest alerts) optimize timings. NMNF's 1,000 FPOs commercialize extracts; CRISPR screens novel limonoids from *Melia dubia*. Global botanical market (USD 8B by 2030) aligns with EU Green Deal imports; India eyes 15% share via PKVY exports. Extension via 5 lakh Krishi Sakhis and digital twins accelerates 30% adoption by 2030.

## Conclusion

Botanical pesticides elegantly fuse ancestral lore with cutting-edge agronomy, delivering 70–96% control sans ecological debt (Agale *et al.*, 2019; War *et al.*, 2014). NMNF/PKVY architectures, bolstered by 2025 Bill reforms, catalyze chemical-free metamorphosis—slashing inputs 50%, incomes up 15–25%, resilience amplified. Conquering standardization via nano-tech and training unlocks their promise for India's natural farming renaissance.

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## Geographical Indications (GI) of Spices and Plantation crops

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Plantation and spice crops are important commercial crops cultivated under specific agro-climatic conditions. Their unique quality and characteristics are largely influenced by the climate and geographical conditions of the regions where they are grown. Since these crops are not produced uniformly across the country, adulteration and quality deterioration have become common, reducing consumer confidence and market value. In this context, Geographical Indications (GI) play a significant role in preserving the authenticity, quality, and uniqueness of these products. Among GI-registered horticultural crops, plantation crops, spices, and medicinal and aromatic plants together account for nearly 36% of the total registrations. Prominent GI-tagged crops include coffee, tea, coconut, chilli, turmeric, ginger, cardamom, Tejpat (Indian bay leaf), jasmine, betel vine, and kewda. While GI registration has expanded considerably in the plantation and spice sectors, medicinal and aromatic crops remain underrepresented, highlighting the need for greater awareness among farmers and producers about the benefits of GI protection in enhancing production, marketability, and rural livelihoods.

### What is a GI tag?

A **Geographical Indication (GI)** is a distinctive sign used to identify products that originate from a specific geographical area and derive their unique quality, reputation, or characteristics from that location. It is a type of intellectual property recognized by the **World Intellectual Property Organization (WIPO)**. GI protection is available for natural products, agricultural commodities, handicrafts, textiles, food products, and certain manufactured goods.

### Who issues GI Tag in India?

The GI signs or tags are issued as per the geographical indication of goods (Registration and Protection Act, 1999). The geographic indication registry is under the Department of Industrial Policy and Promotion, Ministry of Commerce and Industry and it is responsible for issuing GI tags in India.

Darjeeling Tea was the first product that was issued a GI tag in India (2004-05).

### Objectives of GI Tag

1. Safeguard traditional agricultural products and their unique regional identity.
2. Protect registered product names from misuse and illegal copying.
3. Provide better economic returns and improve the livelihood of farmers and producers.
4. Increase the export potential of GI-certified products in global markets.
5. Preserve the cultural and geographical identity of a particular region.



### Significance of GI Tag

**Increases Export Opportunities** – Helps GI-tagged products gain better recognition and demand in international markets.

**Preserves Traditional Heritage Authentic Products-** Prevents unauthorized people from using the registered GI name.

**Maintains Product Quality-** Ensures that the product meets the quality standards associated with its geographical origin.

**Builds Consumer Trust-** Provides consumers with reliable information about the product's origin, quality, and authenticity.

**Improves Farmers' Income-** Genuine producers receive better prices due to the product's reputation and quality.

**Promotes Fair Trade-** Creates a transparent market that benefits both producers and consumers.

**Strengthens Regional Identity-** Gives recognition to products that are unique to a particular geographical area.

**Supports Rural Development-** Encourages employment, local businesses, and sustainable economic growth in rural regions.

### GI Registration process

**Submission of Application-** The applicant submits the GI registration application with all required documents to the GI Registry.

### Some GI-Tagged Spices of India

| Spice        | GI Region         | State     | Photos                                                                                |
|--------------|-------------------|-----------|---------------------------------------------------------------------------------------|
| Black pepper | Malabar Pepper    | Kerala    |  |
| Turmeric     | Lakadong Turmeric | Meghalaya |  |

**Scrutiny and Examination-** The GI Registry examines the application to verify that it meets all legal requirements.

**Publication in the GI Journal-** If the application is accepted, it is published in the Geographical Indications Journal for public notice.

**Opposition Stage-** Any person may raise objections within the prescribed period if they believe the registration should not be granted.

**Grant of Registration-** If no valid opposition is received (or objections are resolved), the GI Registry issues the registration certificate.

**Validity and Renewal-** The GI registration remains valid for 10 years and can be renewed every 10 years to continue legal protection.

### Importance of GI Tag in Agriculture

#### Benefits to Farmers

- Higher income employment generation.
- Protection from fake products.
- Strong market identity.
- Better market price.

#### Benefits to Consumers

- Assurance of genuine products
- Authentic origin.
- Increased trust





|                        |                       |            |                                                                                       |
|------------------------|-----------------------|------------|---------------------------------------------------------------------------------------|
| Turmeric               | Erode Turmeric        | Tamil nadu |    |
| Green Cardamom (Coorg) | Coorg                 | Karnataka  |    |
| Ginger                 | Sikkim Large Cardamom | Sikkim     |    |
| Garlic                 | Vellore Garlic        | Tamil nadu |    |
| Cumin                  | Kutch Cumin           | Gujarat    |    |
| Chilli                 | Khola Chilli          | Goa        |   |
| Chilli                 | Byadagi Chilli        | Karnataka  |  |
| Cinnamon               | Ceylon Cinnamon       | Kerala     |  |

### Some GI-Tagged Plantation crop of India

| Plantation crops            | GI Region    | State          | Photos                                                                                |
|-----------------------------|--------------|----------------|---------------------------------------------------------------------------------------|
| Darjeeling Tea              | Darjeeling   | West Bengal    |  |
| Araku valley Arabica Coffee | Araku Valley | Andhra Pradesh |  |
| Eathomozhy Tall Coconut     | Eathomozhy   | Tamil Nadu     |  |



|                         |           |                  |                                                                                       |
|-------------------------|-----------|------------------|---------------------------------------------------------------------------------------|
| Panruti cashew Nut      | Cuddalore | Tamil Nadu       |    |
| Kangra Tea              | Kangra    | Himachal pradesh |    |
| Nilgiri Tea             | Nilgiris  | Tamil Nadu       |    |
| Arecanut (Sirsi supari) | Sirsi     | Karnataka        |    |
| Coorg green Cardamom    | Coorg     | Karnataka        |    |
| Assam orthodox Tea      | Assam     | Assam            |  |
| Bastar Arabica Coffee   | Bastar    | Chhattisgarh     |  |

### Challenges of GI Tagged Products

Despite their many advantages, GI-tagged products face several challenges. Many farmers are not aware of the benefits and registration process of GI tags. Poor marketing facilities reduce the reach of these products in national and international markets. Counterfeit products damage the reputation of genuine GI products. Limited export infrastructure restricts global trade opportunities, while high certification costs make GI registration difficult for small producers. In addition, climate change affects production and the quality of GI products, creating further challenges for their growth and sustainability.

### Conclusion

Geographical Indication (GI) products are known for their unique quality and authenticity because they are produced in specific regions. GI registration provides legal protection, increases the market value of products, and prevents misuse of their names. It also helps in branding, marketing, and promoting exports. Although many spices, plantation, medicinal, and aromatic crops have received GI tags, greater awareness and more registrations are still needed. Overall, GI tags improve farmers' income, support regional economic development, and strengthen India's economy.



# Organic Fertilizers for Sustainable Agriculture and a Greener Environment

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The increasing degradation of soil resources, rising agricultural pollution, and intensifying climate change impacts have highlighted the importance of adopting sustainable agricultural practices. Organic fertilizers, including compost, vermicompost, farmyard manure, green manures, biofertilizers, and crop residue amendments, are recognized as environmentally sustainable alternatives to synthetic fertilizers. These organic inputs improve soil physicochemical properties, enhance microbial activity, and facilitate gradual nutrient release, thereby minimizing nutrient losses and reducing environmental contamination. Long-term studies have demonstrated that organically managed soils generally exhibit higher soil organic carbon content and greater biological activity than conventionally managed systems. Furthermore, the application of organic fertilizers contributes to carbon sequestration, decreases reliance on industrial chemical fertilizers, and may improve crop quality and nutritional value. Despite challenges related to nutrient variability and transitional yield responses, Integrated Soil Fertility Management (ISFM) provides a balanced approach for sustainable nutrient management. Overall, organic fertilization represents a key strategy for promoting environmentally resilient and sustainable agricultural systems.

## Introduction

Although agriculture has been the foundation of human civilization for more than 10,000 years, the very mechanisms that support the world's food supply are now among the main causes of land and water degradation. Hundreds of millions of people were spared starvation thanks to the widespread use of synthetic chemical fertilizers during and after the Green Revolution in the middle of the 20th century. However, these short-term benefits have resulted in long-term ecological debts, such as decreased soil organic matter, collapsing microbial biodiversity, nitrate contamination of rivers and groundwater, eutrophication of freshwater and coastal ecosystems, and a significant contribution to greenhouse gas emissions from the production of fertilizers and their field-level application (Diacono and Montemurro, 2010; FAO, 2021). The bulk of the world's nitrogen fertilizers are produced using the Haber-Bosch process alone, which consumes between 1% and 2%

of the world's energy and contributes significantly to industrial CO<sub>2</sub> emissions (Lal, 2004). As the world's population reaches 10 billion by 2050, humanity must simultaneously produce 50-70% more food and undo the environmental harm caused by agriculture in the 20th century (FAO, 2021). Over one third of the world's land area is already affected by soil degradation, which is projected to cost USD 40 billion a year in lost agricultural output due to erosion, compaction, acidity, salinization, and organic matter depletion (Lal, 2004). In light of this, organic fertilizers have resurfaced as technologically advanced, scientifically proven, and environmentally essential instruments for farming in the future. They are an advanced set of biological inputs that harness natural nutrient cycles rather than a mere return to pre-industrial methods (Diacono & Montemurro, 2010). Long-term studies show that organic soil management restores biological fertility, lowers environmental pollution, sequesters atmospheric carbon, and promotes more resilient and profitable



farming systems (Mäder et al., 2002; Poeplau and Don, 2015). This article covers in detail the main types of organic fertilizers, their agronomic and environmental advantages, the practical obstacles to their use, and the technical and policy solutions required to hasten the world's shift to more sustainable food production systems.

### What Are Organic Fertilizers?

Organic fertilizers are nutrient-containing substances derived solely from biological sources, such as composted organic debris, animal manures, plant residues, and living microbial preparations. Organic fertilizers release nutrients gradually through microbial decomposition, in contrast to synthetic fertilizers that provide concentrated, instantly soluble minerals prone to volatilization and leaching (Diacono and Montemurro, 2010). In addition to minimizing nutrient losses to the surrounding environment and synchronizing nutrient supply with crop demand, this slow-release approach nourishes the rich biological ecology within the soil itself (Mäder et al., 2002).

The following describes the main types of organic fertilizers:

**1. Compost:** Rich in humus, macro- and micronutrients, and a variety of soil microbes, compost is produced through the controlled aerobic decomposition of organic wastes, such as crop residues, kitchen scraps, and farmyard materials (Diacono & Montemurro, 2010). Regular application of compost dramatically improves soil water retention, structural stability, and biological activity. On-farm composting simultaneously diverts organic waste from burning or landfill disposal, thereby reducing both particulate air pollution and methane emissions from open waste decomposition.

**2. Vermicompost:** This method uses earthworms, mainly *Eisenia fetida* and *Lumbricus rubellus*, to accelerate the breakdown of organic waste into a product rich in humus and nutrients. In terms of

plant-available nitrogen, phosphate, and potassium, vermicompost routinely outperforms traditional compost and has noticeably larger populations of beneficial microbes (Iqbal et al., 2024). One of the most effective organic amendments available to modern agriculture, its application enhances soil aeration, drainage, aggregate stability, and the inhibition of soil-borne diseases (Iqbal et al., 2024).

**3. Green Manures and Cover Crops:** Soybean, cowpea, clover, Dhaincha (*Sesbania spp.*), sunn hemp, and field pea are examples of leguminous plants that are planted expressly to be added to the soil either before or after they reach maturity. Through symbiotic nitrogen fixation with *Rhizobium* bacteria in specialized root nodules, these crops can fix between 50 and 200 kg N/ha directly from atmospheric nitrogen (Aasfar et al., 2021). Their incorporation into the soil simultaneously adds significant quantities of organic matter, improves soil structure, and contributes measurably to soil carbon sequestration (Poeplau and Don, 2015).

**4. Farmyard Manure (FYM):** Recognized as a fundamental component of traditional agricultural practices globally, FYM comprises livestock excreta, liquid waste, and bedding materials such as straw, sawdust, or desiccated foliage. It supplies a comprehensive array of macronutrients and micronutrients including nitrogen, phosphorus, potassium, calcium, magnesium, sulfur, and various trace elements while enhancing soil quality by introducing organic carbon and diverse microbial communities (Diacono and Montemurro, 2010). The efficacy of FYM varies significantly with factors such as animal species, dietary composition, storage conditions, and the extent of prior composting, with well-composted FYM demonstrating markedly greater effectiveness upon application to agricultural fields compared to fresh manure.

**5. Biofertilizers:** Biofertilizers are formulations containing live or dormant microorganisms including *Rhizobium*, *Azotobacter*, *Azospirillum*, Phosphate Solubilizing Bacteria (PSB), and arbuscular



mycorrhizal fungi that inhabit the plant rhizosphere and facilitate nutrient uptake through mechanisms such as biological nitrogen fixation, phosphate solubilization, and the synthesis of plant growth-promoting hormones (Aasfar et al., 2021). These formulations are recognized for their environmental sustainability, economic viability, and scalability for industrial production. The synergistic use of biofertilizers alongside organic amendments significantly enhances nutrient availability and optimizes plant growth responses beyond what either component can achieve when applied independently (Aasfar et al., 2021).

**6. Crop Residue Mulches:** Reintroducing post-harvest residues including straw, stover, husks, and

*Table 1. Key comparative differences between organic and chemical fertilizers across agronomic and environmental parameters.*

| Parameter                | Organic Fertilizers                                       | Chemical Fertilizers              |
|--------------------------|-----------------------------------------------------------|-----------------------------------|
| Source                   | Biological/natural origin                                 | Industrially synthesized          |
| Nutrient Release         | Slow, sustained release                                   | Rapid, immediately soluble        |
| Soil Biological Activity | Enhances microbial diversity (Mäder et al., 2002)         | Gradual decline over time         |
| Environmental Risk       | Low leaching / runoff risk                                | High nitrate leaching & runoff    |
| Carbon Footprint         | Low; sequesters carbon (Lal, 2004)                        | High; energy intensive production |
| Cost to Farmer           | Low; on-farm producible (FAO, 2021)                       | High; market & price volatile     |
| Crop Quality             | Higher phytochemicals (Worthington, 2001)                 | Yield-focused; variable quality   |
| Soil Structure           | Improves aggregate stability (Diacono & Montemurro, 2010) | Neutral to negative long-term     |

vine fragments onto the soil surface facilitates the recycling of inherent nutrients, inhibits weed proliferation, conserves soil moisture, regulates soil surface temperature fluctuations, and provides a sustained energy source for soil-dwelling organisms (Diacono and Montemurro, 2010). The incineration of crop residues, a harmful practice still prevalent in South and Southeast Asia, negates all of the aforementioned benefits while emitting substantial quantities of CO<sub>2</sub>, N<sub>2</sub>O, black carbon, and other harmful pollutants into the atmosphere (FAO, 2021).

### Organic vs. Chemical Fertilizers: A Comparative Overview





## **Benefits of Organic Fertilizers for Sustainable Agriculture**

### ***A. Restoring Soil Health and Biological Diversity***

Soil is much more than an inert physical medium it ranks among the planet's most biologically intricate ecosystems, hosting over one billion microbial cells per gram of healthy topsoil (Mäder et al., 2002). Bacteria, fungi, actinomycetes, protozoa, nematodes, and earthworms form complex food webs that collectively facilitate nutrient cycling, the breakdown of organic matter, the suppression of soil-borne diseases, and the formation of stable soil aggregates. Years of reliance on synthetic fertilizers, coupled with intensive tillage and broad-spectrum pesticides, have significantly diminished this biological richness across the world's most intensively cultivated soils (Diacono and Montemurro, 2010). By supplying a continuous flow of organic carbon and a variety of nutrients, organic fertilizers serve as the primary energy and substrate source for this subterranean ecosystem. The significant DOK (Dornach Organic biodynamic and Conventional) long-term study conducted in Switzerland by Mäder et al. (2002) which lasted over 21 years provided conclusive evidence that soils managed organically contained 40% more microbial biomass, considerably higher populations of earthworms, and significantly increased soil organic carbon (SOC) compared to conventionally managed plots receiving the same nutrient inputs. Enhanced SOC not only nourishes soil life but also boosts aggregate stability, water infiltration, and the soil's ability to retain and gradually supply both water and nutrients to crops (Diacono and Montemurro, 2010).

### ***B. Reducing Pollution and Protecting Freshwater Ecosystems***

The excessive use of synthetic nitrogen fertilizers is the leading human-induced cause of nitrate pollution in rivers, lakes, and aquifers globally (FAO, 2021). Nitrate leaching from agricultural lands directly

contributes to the eutrophication of freshwater bodies and coastal areas a process in which excessive nutrient enrichment leads to algal blooms that deplete dissolved oxygen and result in the death of aquatic life. In India alone, the use of nitrogen fertilizers has surged sixfold since 1970, yet measurable improvements in soil health have plateaued in numerous districts, highlighting significant inefficiencies and environmental repercussions (FAO, 2021). The slow-release nature of organic fertilizers inherently limits the levels of immediately soluble nutrients in the soil solution, thus minimizing both nitrate leaching and phosphorus runoff into aquatic systems (Diacono and Montemurro, 2010). Moreover, replacing synthetic nitrogen derived from the Haber-Bosch process with biological nitrogen fixation via legume cover crops and Rhizobium inoculants eliminates a major source of industrial greenhouse gas emissions and reduces the substantial energy expenditure associated with synthetic fertilizer production (Lal, 2004).

### ***C. Enhancing Crop Quality and Nutritional Value***

An expanding body of research indicates that crops grown organically consistently exhibit higher levels of health-promoting secondary metabolites such as polyphenols, flavonoids, ascorbic acid, carotenoids, and essential minerals than those cultivated with conventional synthetic fertilizers (Worthington, 2001). The balanced, slow-release nutrition provided by organic amendments fosters steady vegetative growth under reduced nutrient stress, resulting in crops that accumulate greater amounts of antioxidants and phytochemicals as part of their natural stress response mechanisms. Worthington (2001) conducted a thorough meta-analysis of 41 published studies and found that organically produced crops contained, on average, 27% more vitamin C, 29% more magnesium, 21% more iron, and 13.6% more phosphorus than their conventionally grown counterparts. Additionally, the postharvest shelf life and firmness of organic produce are enhanced by stronger cell wall formation



resulting from balanced nutrition. Furthermore, organically certified produce often commands significant market premiums, typically 20-40% higher than conventional counterparts, thereby improving farmers' incomes and promoting sustainable practices (FAO 2021).

#### ***D. Climate Resilience and Carbon Sequestration***

Climate change is fundamentally altering agricultural systems worldwide increasing average temperatures, making monsoon and rainfall patterns more erratic, and raising the frequency of extreme weather events, all of which are already diminishing yields and jeopardizing food security in at-risk areas (FAO, 2021). Soils rich in organic matter exhibit significantly greater resilience to these pressures. High humus content greatly enhances a soil's capacity to retain plant-available water, allowing crops to endure and remain productive during droughts that can lead to near-total crop failure in degraded soils with low organic carbon. Lal (2004) estimated the global potential for soil carbon sequestration through enhanced organic management to be between 0.9 and 1.85 Pg C annually - which corresponds to 5-15% of yearly global fossil fuel emissions - thus representing a potent and technologically feasible climate mitigation approach. Supporting this, Poeplau and Don (2015) conducted a meta-analysis of 139 plots across 37 global locations and verified that incorporating cover crops as green manures sequesters carbon at an average annual rate of  $0.32 \pm 0.08$  Mg C/ha/year in the topsoil. The global '4 per 1000' initiative, introduced at COP21 in Paris, further emphasized that increasing global soil organic carbon by just 0.4% each year could theoretically counterbalance the entire net annual rise in atmospheric CO<sub>2</sub>. Consequently, transitioning to organic soil management is not only an agronomic approach but also a vital and underutilized element of global climate policy (Lal, 2004; Poeplau and Don, 2015).

#### ***E. Economic Empowerment of Smallholder Farmers***

In regions such as South Asia, Sub-Saharan Africa, and others where smallholder farmers are prevalent, the expense of synthetic fertilizers can account for 30 to 50% of total farm income (FAO, 2021). The global surge in fertilizer prices during 2021-2022, when urea prices tripled in just 18 months due to spikes in natural gas prices, starkly illustrated the dependence and vulnerability of small-scale farming systems to synthetic input markets they cannot control (FAO, 2021). Organic fertilizers like compost, vermicompost, and green manures can be made right on the farm using materials that are already available locally, such as leftover crops, kitchen waste, animal dung, and leafy plants, at a cost that is a fraction of what chemical fertilizers demand. Research has repeatedly shown that when farmers replace even a quarter to half of their synthetic nitrogen with biological sources like biofertilizers and green manures, their yields hold steady while their costs drop noticeably (Aasfar et al., 2021). Governments and development organizations that have genuinely invested in teaching smallholder farmers how to compost and work with biofertilizers have seen real improvements in household incomes, food security, and the long-term health of the soil (FAO, 2021).

That said, organic fertilizers come with real, honest challenges that deserve acknowledgment rather than being brushed aside (Diacono and Montemurro, 2010). For starters, organic materials carry far fewer nutrients per kilogram than chemical fertilizers, and their nutrient content varies from batch to batch. A farmer might need to spread five to ten tonnes of compost across a single hectare just to match what a few hundred kilograms of synthetic fertilizer would deliver, a logistical headache, especially for smallholders with no truck or machinery (Diacono and Montemurro, 2010). Switching from chemical to organic farming is also not immediate. The soil needs roughly two to three years to rebuild its microbial life and restore its



natural nutrient cycles. During that period, yields can dip by five to twenty percent, a loss that farmers living on tight margins simply cannot absorb without financial support or crop insurance (Mäder et al., 2002).

Biofertilizers, essentially living microorganisms packaged for application, have their own problems. In tropical climates with high heat, humidity, and no reliable cold storage, keeping these products alive and effective is genuinely difficult. When quality is inconsistent, which it often is in developing markets, farmers lose confidence in the products entirely, and that is a completely understandable response (Aasfar et al., 2021).

Knowledge is another gap that cannot be ignored. Many farmers, particularly older ones or those in remote areas, lack access to reliable guidance on composting, vermicomposting, or biofertilizer use. Agricultural extension services across most low- and middle-income countries are chronically underfunded, leaving most farmers without anyone to turn to for professional advice.

Addressing all of this requires a coordinated effort, including policy subsidies that make organic inputs genuinely competitive with chemical ones, public investment in biofertilizer research and quality control, properly resourced extension services, and market systems that reward organic farmers through certification and fair pricing (FAO, 2021). The Integrated Soil Fertility Management approach, which combines organic amendments with small, targeted doses of mineral fertilizer where needed, offers the most practical and immediately workable path for the majority of the world's farmers who are not yet in a position to go fully organic (Diacono and Montemurro, 2010).

Organic fertilizers are far more than an alternative to synthetic inputs. They are the biological foundation of a more honest and sustainable relationship between farming and the natural world.

By restoring soil health, reducing pollution, capturing atmospheric carbon, strengthening farms against climate shocks, improving the nutritional quality of food, and lowering costs for farmers who can least afford rising input prices, organic fertilizers deliver benefits that extend far beyond any single field. The evidence built up over decades of careful research is clear: farming with organic soil management not only maintains productivity but actively rebuilds it, while steadily reducing the environmental damage that defined twentieth-century agriculture. The Integrated Soil Fertility Management approach offers a practical and realistic bridge between what is ideal and what is achievable for most farmers today. What is needed now is for policymakers, researchers, businesses, and farmers themselves to act with the seriousness and urgency this moment truly calls for. The soil beneath our feet is the most valuable and the most threatened living resource we have. Taking care of it through organic management is both our greatest agricultural opportunity and one of our most urgent environmental responsibilities.

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# Organic Aquaculture: A Sustainable Approach to Restoring Environment

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Organic aquaculture has emerged as a sustainable production system that integrates environmental stewardship, animal welfare, and food safety while addressing the ecological challenges associated with conventional aquaculture. By eliminating the use of synthetic chemicals, antibiotics for routine growth promotion, genetically modified organisms, and artificial feed additives, organic farming promotes ecosystem health and enhances the production of safe, high-quality aquatic food. This article presents the fundamental principles and practices of organic aquaculture, including appropriate site selection, pond preparation, procurement of healthy seed, organic feed management, water quality maintenance, disease prevention through biosecurity and natural remedies, and organic certification procedures in India. The role of accredited certification agencies and adherence to recognized organic standards are also highlighted. Adoption of these practices contributes to biodiversity conservation, efficient resource utilization, improved fish welfare, and reduced environmental pollution. Organic aquaculture therefore represents a resilient and environmentally responsible approach to fish farming, supporting long-term sustainability, consumer confidence, and the economic well-being of aquaculture producers.

## Introduction

In recent years, concerns regarding food safety have intensified due to the increasing prevalence of food adulteration, fraudulent practices, and other unethical activities within the marketplace aimed at maximizing commercial profits. This growing awareness has significantly influenced consumer purchasing behaviour, with an increasing preference for chemical-free and naturally produced food products, for which consumers are willing to pay a premium price. Organic aquaculture is eco-friendly farming of aquatic organisms such as fish, shrimp, bivalves, and aquatic plants using environmentally sustainable practices that avoid the use of synthetic chemicals, antibiotics, and chemical fertilizers to produce safe, high-quality seafood while conserving aquatic ecosystems and biodiversity.

Furthermore, organically and sustainably produced fish have gained considerable acceptance

among health-conscious consumers, creating opportunities for producers to access high-value niche markets. Consequently, the adoption of organic aquaculture practices enables farmers to secure premium prices for their products, thereby enhancing farm profitability while simultaneously promoting environmental stewardship and sustainable food systems.



Fig. 1. Fish farm





### Key features Organic aquaculture: key features

Organic aquaculture follows natural and environmentally friendly farming practices to produce safe and high-quality fish. It avoids the routine use of synthetic chemicals, antibiotics, and genetically modified organisms (GMOs). Fish are provided with organic feed, optimum water quality, and adequate space to support their health and welfare.

The farming system also focuses on conserving biodiversity, reducing pollution, and using natural resources responsibly. In addition, organic aquaculture follows certification standards to ensure product quality and build consumer confidence.

### Principles of Organic aquaculture:

- Genetically modified fish and feed ingredients are not permitted. Organic feed should be derived from certified plant-based sources.
- Fish should be stocked at sustainable densities to ensure welfare, reduce stress, and maintain ecological balance.
- Only certified organic feed, fertilizers, and approved natural inputs should be used; synthetic additives are prohibited.
- Soil and water fertility should be maintained through organic manures and natural nutrient recycling rather than inorganic fertilizers.
- The use of synthetic pesticides, herbicides, and harmful chemicals is prohibited to protect biodiversity and ecosystem health.
- Energy consumption and intensive farming practices should be minimized to promote environmental sustainability.
- Fish health should be maintained through good husbandry, biosecurity, balanced nutrition,

probiotics, and herbal remedies instead of routine antibiotics.

- Harvesting, processing, storage, and transportation must comply with organic standards to ensure product integrity and traceability.



Fig.2. Features of Organic farming

### Guidelines for Initiating Organic Aquaculture Production

#### ➤ Pond Preparation

Proper pond preparation is essential for successful organic aquaculture. First the pond should be drained completely and allowed to dry. Drying helps eliminate harmful organisms and improves the condition of the pond bottom. Any aquatic weeds, accumulated organic debris, dead fish, and other waste materials should be removed to maintain a clean environment. Lime should then be applied at the recommended dose based on the results of a soil analysis to improve soil quality and stabilize the pond ecosystem. Finally, the pond should be filled gradually with clean, uncontaminated water, creating suitable conditions for stocking healthy fish seed. Organic manures are applied to improve soil fertility and encourage the growth of natural fish food, creating a healthy environment for fish culture.

#### ➤ Seed Selection for organic aquaculture and Stocking



Fish seed should be procured exclusively from accredited and reputable hatcheries to ensure high quality and traceability. Only healthy, active fingerlings exhibiting normal swimming behaviour and free from physical injuries or deformities should be selected for stocking. Seed showing any signs of disease, stress, or abnormality should be rejected to minimize the risk of disease transmission. Before stocking, the fingerlings should be gradually acclimatized to the pond water by slowly equalizing the water temperature and other environmental conditions, thereby reducing stress and improving survival.

### ➤ Feeding Management

Fish are fed with organically produced feed ingredients that are free from synthetic additives and

genetically modified materials. Natural and supplementary feeds are provided to meet their nutritional requirements and support healthy growth.

### Criteria required for organic feed:

- Use certified organic feed ingredients whenever possible.
- GMOs, synthetic growth promoters, artificial pigments, and chemically synthesized feed additives are not permitted under organic certification standards.
- Natural, sustainable feed ingredients are preferred to promote fish health and protect the environment.

**Table.1 Sources of feed for organic aquaculture**

| Plant Protein Sources                                                                    | Natural Protein Sources                                                         | Energy Sources                                                          | Natural Feed Additives                                                                                                           | Natural Mineral Sources          | Animal Protein Sources<br>(Permitted under some organic standards)          | Binders                                                         |
|------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------|-------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------|----------------------------------|-----------------------------------------------------------------------------|-----------------------------------------------------------------|
| Soybean Meal<br>Groundnut (Peanut) Cake<br>Mustard Cake<br>Sesame Cake<br>Sunflower Cake | Azolla<br>Spirulina<br>Duckweed<br>Moringa<br>Leaf<br>Powder<br>Alfalfa<br>Meal | Rice<br>Bran<br>Wheat<br>Bran<br>Maize (Corn)<br>Meal<br>Broken<br>Rice | Probiotics<br>Prebiotics<br>Yeast<br>Culture<br>Garlic<br>Powder<br>Turmeric<br>Powder<br>Ginger<br>Powder<br>Herbal<br>Extracts | Rock Salt<br>Limestone<br>Powder | Fish Meal<br>Fish Oil<br>Black Soldier Fly<br>Larvae Meal<br>Earthworm Meal | Wheat<br>Flour<br>Tapioca<br>Flour<br>Rice Flour<br>Corn Starch |

### Organic feed manufactures:

- BioMar – Organic fish feed (Europe)
- Skretting – Organic aquaculture feeds
- Aller Aqua – Organic feed for freshwater and marine fish
- Le Gouessant Aquaculture – Organic aquafeeds
- Aqua Organic Solutions (regional markets)



### ➤ Water Quality Management

Maintaining good water quality is essential in organic aquaculture. Water quality is monitored regularly, and biological methods such as probiotics and natural filtration are used to maintain a healthy aquatic environment.

### ➤ Disease Management

Disease management in organic aquaculture emphasizes prevention rather than treatment. In the event of a disease outbreak, the affected fish should first be examined carefully to identify the causative agent, followed by appropriate diagnostic tests to determine the severity of the infection. Based on the diagnosis, approved natural remedies such as neem oil, turmeric, ginger, probiotics, and herbal preparations may be used to support fish health and control disease. Infected fish should be promptly isolated in separate quarantine tanks to prevent the spread of pathogens to healthy stocks. Maintaining good water quality, providing balanced organic nutrition, implementing strict biosecurity measures, and following best management practices are essential for minimizing disease occurrence and reducing dependence on synthetic chemicals and antibiotics.

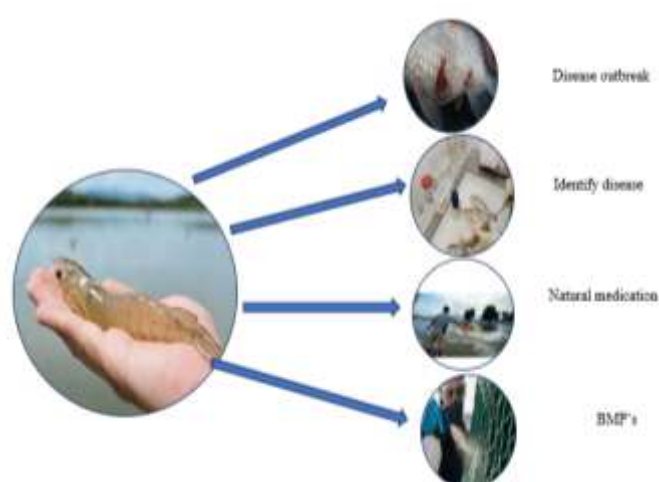


Fig.3. Disease management in organic aquaculture

### Certification process in organic aquaculture

The certification process for organic aquaculture involves a series of systematic steps designed to ensure compliance with recognized organic production standards. These stages verify that aquaculture practices meet environmental, animal welfare, and traceability requirements before certification is granted.

#### 1. Initial Information Exchange

During this stage, the producer receives comprehensive guidance on the technical requirements, certification standards, documentation procedures, and regulatory obligations associated with organic aquaculture. A preliminary questionnaire is also completed to collect essential information regarding the farming system, management practices, and production history. This assessment helps determine the farm's readiness for the certification process.

#### 2. Pre-Evaluation Visit

A pre-evaluation visit is conducted to assess the existing farming conditions and determine the farm's suitability for conversion to organic production. During this visit, evaluation of the current management practices, infrastructure, and operational procedures while discussing the necessary modifications required to achieve compliance with organic standards. Based on these observations, a conversion plan is developed outlining the actions and timeline needed for successful transition.

#### 3. On-Site Inspection

Following the pre-evaluation stage, the certification body schedules a formal on-site inspection. During the inspection, all aspects examination of the production system will takes place, including pond



management, seed sourcing, feed inputs, water quality management, animal health practices, record keeping, and traceability systems. The observations and findings are documented in a detailed inspection report, which is subsequently submitted to the certification authority for technical evaluation.

#### 4. Final - Certification

The certification committee reviews the inspection report and supporting documents. If the farm meets organic standards, certification is granted. Annual inspections and renewal ensure continued compliance.

Organizations or bodies that provide organic certifications for aquaculture in India

1. Nodal agency - Agricultural and Processed Food Products Export Development Authority (APEDA)
2. organic certification system - National Programme for Organic Production (NPOP)
3. Food Safety and Standards Authority of India (FSSAI)
4. National Accreditation Body (NAB)

#### Conclusion:

Organic aquaculture represents a sustainable production system that avoids the use of synthetic chemicals, artificial growth promoters, and other harmful inputs, while promoting environmentally responsible farming practices. By emphasizing ecological balance, animal welfare, and the efficient use of natural resources, it offers a viable alternative to conventional aquaculture. The adoption of organic aquaculture contributes to the restoration of degraded

aquatic ecosystems, enhances biodiversity conservation, and improves the long-term sustainability of fish production. As the demand for safe, high-quality, and environmentally friendly seafood continues to grow, farmers and stakeholders should embrace organic aquaculture practices to safeguard ecosystem health, ensure sustainable livelihoods, and preserve aquatic resources for future generations.

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# The Gene Bank Mission: The Vital Role of Gene Banks in Securing Our Agricultural Future

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**"The earth, the air, the land, and the water are not an inheritance from our forefathers but on loan from our children."**

*Dr. A.P.J. Abdul Kalam*

In an era defined by accelerating climate change, deepening biodiversity loss, and mounting food insecurity, gene banks stand as silent sentinels preserving the genetic diversity that underpins life on Earth. These repositories of seeds, tissues, and genetic material are not merely scientific marvels; they are critical tools for ensuring the survival of agriculture, ecosystems, and humanity itself. In India, a country with millennia of agricultural heritage and a population exceeding 1.4 billion, gene banks are fast becoming indispensable components of sustainable development. Globally, they serve as insurance against extinction and as springboards for innovation.

This article delves into the significance of gene banks, presents the latest verified statistics and use cases, examines government initiatives in India, draws comparisons between the Indian and global scenarios, highlights global best practices, addresses persistent challenges, and proposes innovative pathways forward, including how financial institutions can leverage this opportunity to bolster agribusiness.

## The Essence of Gene Banks

A gene bank is a biorepository that collects, conserves, and manages genetic material including seeds, pollen, tissues, or DNA from plants, animals, and microorganisms. For agriculture, plant gene banks are the most prominent, safeguarding crop varieties and their wild relatives. They ensure genetic diversity, which is vital for breeding resilient crops capable of withstanding pests, diseases, and shifting climatic conditions.

As of 2025, the global network of gene banks holds millions of accessions, forming a collective safety net for food security. According to the FAO (2025), national gene banks alone store 84 percent of global plant resources and form the foundation of a worldwide conservation system that includes international and regional partners. The CGIAR (Consultative Group on International Agricultural

Research ) network, which operates eleven gene banks collectively, holds upwards of 700,000 accessions spanning more than 3,000 plant species. All of this material is made openly accessible to researchers, plant breeders, local communities, and farmers alike under the framework of the International Treaty on Plant Genetic Resources for Food and Agriculture (ITPGRFA).

The International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) Gene Resources Unit, established in 1979, maintains 131,557 germplasm accessions sourced from 144 countries. Between 1973 and December 2024, seed samples distributed by the ICRISAT Gene Bank reached researchers across 151 countries, with cumulative distributions exceeding 1.67 million samples.





## Why We Need Gene Banks

The future of our food systems will be built upon the diversity preserved in gene banks. Agricultural adaptation depends on specific genes that confer heat and drought resistance, pest tolerance, or nutritional enhancement to crop varieties. Farmers and breeders confronting the climate emergency must have access to a broad spectrum of diversity that may hold the answers to tomorrow's challenges.

Industrial agriculture has dramatically narrowed the genetic base of food crops. The FAO estimates that modern agriculture caused the loss of approximately 75 percent of crop genetic diversity during the twentieth century. A cattle breed or crop variety, once extinct, cannot be recovered. Gene banks must therefore ensure that their collections remain viable through rigorous quality management protocols, periodic seed regeneration, and investment in modern storage technologies.

Gene banks, however, are far more than repositories of preserved material. They function as active engines of crop improvement, directly feeding genetic diversity into breeding programmes that develop higher-yielding, more resilient, and climate-adapted varieties. The CGIAR Genebanks Accelerator (2025 to 2030) aims to leverage frontier technologies in genomics, artificial intelligence (AI), and cryopreservation to enhance the availability and real-world impact of genetic resources worldwide.

## Gene Banks by the Numbers: Key Global and Indian Statistics

The scale of gene bank operations globally and in India has grown considerably, driven by fresh policy commitments and scientific advances. The following figures reflect the most current verified data available as of early 2026.

## Global Statistics

Over 1,750 national, regional, and international gene banks worldwide are collectively conserving approximately 7.4 million crop sample varieties (FAO, 2025).

The Svalbard Global Seed Vault in Norway, often called the 'Doomsday Vault,' conserved 1,355,591 accessions as of June 2025, with deposits made three times annually from gene banks across every inhabited continent (Wikipedia, 2025; Crop Trust, 2025).

In October 2025 alone, twenty gene banks deposited more than 21,000 seed samples at Svalbard, including first-time contributors from the Philippines and Peru (Crop Trust, October 2025).

National gene banks store 84 percent of global plant resources (FAO, 2025), making them the backbone of international conservation efforts.

The CGIAR's eleven gene banks conserve over 700,000 accessions representing more than 3,000 plant species, freely available as international public goods.

Worldwide gene banks have made nearly one million samples available to users in over 120 countries since 2012.

## India's Statistics

India's National Gene Bank (NGB), established in 1996 by ICAR-NBPGR in New Delhi, currently holds 512,999 total accessions as of May 2026, comprising 430,575 seed accessions, 10,926 cryo-preserved accessions, 613 in-vitro accessions, and 2,150 field gene bank accessions (ICAR-NBPGR Genebank Database, 2026).

The NGB is recognised as the second largest gene bank in the world, preserving 4,71,561 accessions from 2,157 species across cereals (0.17 million), millets (60,600+), legumes (69,200+), oilseeds



(63,500+), and vegetables (30,000 nearly) as of January 2025 (PIB, 2025).

The National Bureau of Animal Genetic Resources (NBAGR) in Karnal, Haryana, conserves over 150 indigenous livestock breeds through cryopreservation of semen and embryos.

As announced in the Union Budget 2025-26 under the theme 'Investing in Innovations,' a second National Gene Bank will be established with capacity for 10 lakh (one million) germplasm lines (Ministry of Finance, GoI, 2025).

### **India's Second National Gene Bank: A Strategic Leap**

Nearly 29 years after India set up its maiden gene bank in 1996, the Union Budget 2025-26 unveiled plans for a second National Gene Bank under the overarching theme of 'Investing in Innovations.' Prime Minister Narendra Modi expanded on this initiative at a post-budget webinar in March 2025, underscoring that the new facility would safeguard the country's genetic heritage and underpin food security for generations to come.

The new gene bank will feature state-of-the-art infrastructure with a conservation capacity of one million germplasm lines, roughly double the current holding of the first NGB. It is designed to serve both public and private sector agencies engaged in crop improvement and genetic resource management, and will provide a redundant, fail-safe storage system for India's irreplaceable germplasm. The Ministry of Agriculture and Farmers Welfare has also indicated that the facility will support biodiversity conservation initiatives for countries in the SAARC and BRICS regions, positioning India as a leader in global agricultural diplomacy (PIB, 2025).

Key objectives of the second NGB include assuring future food and nutritional security, strengthening climate-resilient crop breeding, supporting both the public and private sectors in the management and

utilisation of genetic resources, and serving as a redundant safety system for India's irreplaceable germplasm stock.

### **Government of India Schemes Supporting Gene Banks**

The Indian government recognises gene banks as pivotal to agricultural resilience and food security. Several national programmes provide institutional and financial support.

**National Gene Bank Initiative (1996):** Managed by ICAR-NBPGR, this facility preserves seeds at minus 20 degrees Celsius for long-term conservation. A network of twelve regional stations undertakes germplasm collection expeditions covering both native and exotic plant genetic resources.

**Rashtriya Krishi Vikas Yojana (RKVY):** This scheme funds research and conservation efforts, including gene bank infrastructure upgrades and the integration of modern digital management tools.

**Mission for Integrated Development of Horticulture (MIDH):** Supports fruit and vegetable gene banks and encourages the conservation of horticultural genetic resources through institutional partnerships.

**National Livestock Mission (NLM):** Bolsters NBAGR's efforts to conserve indigenous animal breeds through cryopreservation and community-based conservation programmes.

**National Gene Fund (NGF):** Operated by the Protection of Plant Varieties and Farmers Rights Authority (PPV&FRA) under the PPV&FR Act of 2001, the NGF functions as a financial backbone, rewarding farmers for conserving traditional varieties and funding research into genetic diversity.

These schemes collectively align with India's commitments to UN Sustainable Development Goals, particularly SDG 2 (Zero Hunger) and SDG 13 (Climate Action).



## India and the Global Scenario: A Comparative View

India's gene banking efforts are substantial, yet they face unique structural challenges when measured against global benchmarks. The NGB is the world's second largest restored gene bank and focuses on conserving indigenous crops such as rice (over 100,000 accessions), wheat, millets, and pulses, reflecting the country's exceptional agrarian diversity. NBAGR covers livestock diversity essential to rural livelihoods.

Globally, gene banks such as the Svalbard Vault, the Millennium Seed Bank in the United Kingdom, and the International Rice Research Institute (IRRI) in the Philippines have set high benchmarks. The Svalbard Vault, with a total storage capacity of 4.5 million seed varieties and 1.35 million accessions already deposited as of mid-2025, operates in natural permafrost conditions that ensure long-term preservation with minimal energy input. The CGIAR network conserves over 700,000 accessions representing more than 3,000 plant species across eleven gene banks worldwide.

India lags in cryopreservation and in-vitro conservation compared to leading nations where these technologies are widely adopted.

Yet India's true competitive advantage rests on something far deeper than infrastructure — its unparalleled biological diversity and the time-honoured, community-led conservation practices that generations of farming communities have sustained through lived agricultural knowledge.

The announcement of the second NGB, along with a growing focus on digital cataloguing and AI-driven analytics, signals a commitment to closing this technology gap.

## Best Practices from Around the World

**Cryopreservation (Norway, France):** The Svalbard Vault and France's Institut de Recherche pour le Développement (IRD) use liquid nitrogen to store genetic material virtually indefinitely. India's ICAR has begun piloting cryopreservation for vegetatively propagated crops such as potato and banana, but scaling remains limited.

**Digital Cataloguing and Genomics (UK, CGIAR):** The Millennium Seed Bank employs Digital Sequence Information (DSI) to track and share genetic data globally. The CGIAR Genebanks Accelerator (2025 to 2030) is systematically genotyping accessions and using AI tools to identify germplasm suited to projected future climates, as highlighted in a 2025 study published in Nature Climate Change.

**AI-Assisted Germplasm Identification (Global):** A 2025 Nature Climate Change study demonstrated how merging genomic and environmental data can identify the best-suited germplasm for future climatic conditions, accelerating the translation of gene bank collections into actionable crop breeding decisions.

**Community Seed Banks (Brazil, Ethiopia):** These decentralised models empower farmers to conserve local varieties. Given that India encompasses more than 600,000 villages, the country holds considerable potential to scale a comparable model by drawing on its existing Krishi Vigyan Kendra network as a ready-made institutional backbone for grassroots implementation.

**Public-Private Partnerships (USA):** Collaboration between gene banks and biotechnology firms accelerates crop improvement programmes. The USDA National Plant Germplasm System, though facing resource pressures in 2025, remains a model for integrating public collections into commercial breeding pipelines.



**Climate-Resilient Breeding (IRRI, Philippines):**

IRRI's gene bank has enabled the development of flood-tolerant and drought-tolerant rice varieties now planted across millions of hectares in Asia. In October 2025, the Philippine Rice Research Institute made its first-ever international safety deposit at Svalbard, placing over 4,000 rice accessions including traditional and climate-resilient varieties, underscoring the urgency of international backup systems.

**Future Seeds Initiative (Colombia):**

The Alliance of Bioversity International and CIAT operates a gene bank in Colombia that integrates genomics, digital phenotyping, and information technologies to identify genes associated with desirable traits, providing plant genetic material free of charge to researchers in many countries.

**Emerging Use Cases: Where Gene Banks Meet Modern Technology**

The role of gene banks is rapidly expanding beyond passive preservation. The following use cases illustrate how genetic repositories are being actively deployed in 2025 to address real-world challenges.

**1. AI-Powered Climate Adaptation Breeding**

The CGIAR Genebanks Accelerator is deploying AI algorithms to analyse genomic and environmental datasets simultaneously, identifying accessions with traits suited to projected future climatic conditions. This approach significantly compresses traditional breeding timelines and enables breeders to make pre-competitive selections from vast collections that would otherwise be impractical to screen manually.

**2. Emergency Germplasm Restoration**

Sudan's civil war led to the looting and destruction of its national seed bank, with over 17,000 seeds affected. However, backup deposits at Svalbard ensured the survival of critical sorghum and pearl millet varieties. In February 2025, Sudan deposited

an additional 2,000+ seed samples at Svalbard, while 22 other seed banks simultaneously made deposits in the same cycle, illustrating the vault's role as a global emergency insurance system (EcoWatch, 2025).

**3. Cultural Heritage Preservation**

The June 2025 Svalbard deposit included seeds representing cultural identity alongside nutritional diversity, ranging from Korea's perilla and adzuki bean to Dutch heritage cabbage varieties and Benin's ancient cereal fonio. This signals an evolving understanding of gene banks not merely as scientific facilities but as custodians of agrarian cultural memory.

**4. Biodiversity for Opportunities, Livelihoods and Development (BOLD)**

Funded by Norway and managed by the Crop Trust, the BOLD project provides grants to gene banks in developing nations to regenerate seeds and back them up at Svalbard. In 2025, Can Tho University in Vietnam made its first-ever deposit of 1,000 Mekong Delta rice samples, including both improved varieties and traditional landraces, facilitated by BOLD funding (Crop Trust, 2025).

**5. Tree Species and Agroforestry Conservation**

CIFOR-ICRAF deposited 120,000 seeds from 13 native African tree species, including the iconic baobab, in February 2025, bringing its cumulative Svalbard contribution to over 1.1 million seeds from 177 species. This reflects a growing recognition that gene bank mandates must extend beyond food crops to encompass agroforestry species critical to ecosystem services.

**6. CRISPR and Genome Editing Integration**

Gene bank accessions are increasingly serving as source material for CRISPR-based and other genome editing approaches. A 2025 *Frontiers in Genome Editing* study highlighted how accessions from gene banks are being used to identify superior alleles for



drought and heat tolerance that are then transferred into elite varieties through precision editing, bypassing lengthy conventional backcross breeding.

## Challenges

**Funding Constraints:** Gene banks require sustained investment for maintenance, staff, seed regeneration, and technology upgrades. Globally, many national gene banks lack adequate resources, and even in high-income countries, the USDA's National Plant Germplasm System faced staff reductions in 2025, raising concerns about the long-term continuity of globally important collections (ScienceDirect, 2025).

**Infrastructure Gaps:** Limited cryopreservation facilities, inadequate cold-chain infrastructure, and power supply vulnerabilities hinder long-term storage reliability, particularly in lower-income countries.

**Awareness Deficit:** Farmers and policymakers frequently undervalue genetic conservation until crisis strikes. Community engagement and extension education remain underinvested globally.

**Climate Threats to Field Gene Banks:** Rising temperatures and erratic precipitation directly threaten field gene banks that maintain clonal crops, fruit trees, and vegetatively propagated species that cannot be stored as seeds.

**Data Management and DSI Policy:** The lack of fully digitised, interoperable records limits global collaboration. Additionally, negotiations over access and benefit-sharing frameworks for Digital Sequence Information remain unresolved at the international level, creating policy uncertainty for users and depositors alike.

**Viability Management:** Seeds must be periodically regenerated to maintain germination rates. Without rigorous viability testing and regeneration protocols, even well-stocked gene banks risk silent attrition of their collections over time.

## Solutions and the Way Forward

**Increased Budget Allocation:** Channelling dedicated funds through RKVY and MIDH to modernise gene bank infrastructure, equip regional stations with cryopreservation units, and automate viability monitoring.

**Renewable Energy Integration:** Solar-powered and energy-efficient cold storage units can address power vulnerabilities, building on precedents set by off-grid seed vaults in remote regions of India.

**AI and Genomics Platforms:** Adoption of AI-driven germplasm characterisation tools, aligned with CGIAR's Genebanks Accelerator model, to translate vast collections into targeted breeding recommendations.

**Farmer Education Campaigns:** Utilising Krishi Vigyan Kendras (KVKs) to promote community seed banking, indigenous variety documentation, and participatory plant breeding.

**Climate Proofing:** Construction of underground or permafrost-style vaults and investment in redundant backup systems mirroring the Svalbard model for India's most irreplaceable germplasm.

**Blockchain Certification:** Deploying blockchain technology to certify gene-bank-derived seeds for authenticity and traceability, enhancing farmer trust and the commercial value of conserved varieties.

**Gene Bank Hubs:** Establishing regional hubs linked to the second NGB and integrating AI to predict crop resilience, optimise regeneration cycles, and facilitate smarter distribution of accessions.

**Mobile Gene Banks:** Deploying refrigerated mobile units to collect and store genetic material from remote and tribal agricultural communities, ensuring inclusivity in conservation.





**Youth Engagement:** Launching a Gene Guardians programme in schools and colleges to build conservation awareness among the next generation of farmers and scientists.

**Global Partnerships:** Deepening collaboration with CGIAR, FAO, and the Crop Trust to access cutting-edge technologies, co-fund conservation activities, and integrate India's collections into global breeding pipelines.

### **Financial Institutions and Agribusiness Opportunities**

Banks and financial institutions stand at a pivotal juncture, poised to transform gene banks from scientific facilities into engines of agribusiness growth.

**Green Loans:** Offering concessional loans to farmers and agribusiness firms utilising gene-bank-sourced resilient varieties, mirroring the green finance frameworks already piloted by major Indian public sector banks.

**Crop Insurance Products:** Designing insurance products tied to gene-bank-supported varieties, enabling actuarial risk models based on documented varietal performance data and thereby reducing premium costs for farmers adopting scientifically backed seeds.

**Investment in Agricultural Biotechnology:** Funding startups and research institutions leveraging gene bank data for hybrid and biofortified seed development, tapping into India's rapidly growing seed market.

**Agri-Entrepreneurship and Microfinance:** Supporting rural entrepreneurs through microfinance and business development services to establish community seed banks, strengthening financial inclusion while building decentralised conservation infrastructure.

**Carbon Credits and Green Finance:** Financing gene bank projects that conserve carbon-sequestering and agroforestry species, aligning portfolios with India's net-zero goals and generating tradeable carbon assets.

**Blended Finance for Second NGB:** Structuring public-private blended finance instruments to co-fund the construction and operation of India's second National Gene Bank, de-risking public investment while enabling private sector participation in biodiversity conservation.

By integrating gene bank services into their lending and investment portfolios, financial institutions can expand their agribusiness scope, boost rural economies, and align with sustainable finance trends that are increasingly shaping global capital allocation.

### **Conclusion**

Gene banks are more than repositories; they are lifelines to a sustainable future. India's strides, from the establishment of the NGB in 1996 to the ambitious second gene bank announced in the Union Budget 2025-26, reflect a deepening national commitment to safeguarding its genetic wealth. The most current data confirm that India's NGB already holds over 512,999 accessions as of May 2026, making it the world's second largest plant genetic resources facility. Globally, the Svalbard Vault has crossed 1.35 million accessions, deposits from conflict zones such as Sudan underscore the vault's indispensable insurance function, and the CGIAR Genebanks Accelerator is deploying AI and genomics at scale to make collections more actionable for climate-smart breeding.

Yet the journey remains fraught with challenges: funding gaps, infrastructure deficits, policy uncertainty over digital sequence information, and the relentless pressure of climate change on field collections demand urgent, coordinated responses. Globally, best practices ranging from AI-assisted



germplasm identification in nature to community-driven seed banking in Ethiopia and Brazil offer a roadmap that India must adapt to its unique context, scale, and aspirations.

Financial institutions stand at a pivotal juncture. By treating gene banks not as cost centres but as sources of agronomic and commercial value, banks, insurers, and investors can turn biodiversity conservation into a driver of inclusive rural growth.

As Dr. Kalam reminded us, the resources of this earth are a loan from our children. Gene banks embody that intergenerational compact. By investing in them today, India can lead the world tomorrow, ensuring food security, ecological balance, and economic prosperity for generations to come.

*"Gene banks are vital to the future of people on Earth, and in a sense, they are much more valuable than ordinary banks."*

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# Inside the Early Life of Plants: Physiology of Seedling Emergence and Growth

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The journey of a plant begins long before we see it rise above the soil surface. Deep inside every seed lies a tiny living embryo, protected by seed coverings and supported by stored food reserves, patiently waiting for the right conditions to begin life. When suitable moisture, temperature, and oxygen levels become available, the seed awakens from dormancy and reactivates its metabolic processes. Enzymes become active, stored nutrients are mobilized, and the first signs of growth slowly emerge. This marks the beginning of one of the most fascinating biological events in the plant world — seedling emergence and early growth. It is during this short, sensitive, and highly critical phase that the young seedling must successfully establish its roots, orient itself toward light, and adapt to its surrounding environment. The success or failure of these early steps ultimately determines whether the plant will survive, thrive, or fail to establish in its habitat.

## Awakening of the Seed: From Dormancy to Activation

Seeds often remain dormant until conditions support germination. When they absorb water through a process called **imbibition**, metabolic activity is reactivated. Enzymes break down stored food reserves in the cotyledons and endosperm, supplying energy for growth.

### During this phase:

- cell division and elongation begin
- the seed coat softens
- the embryo resumes active life

The first visible sign of germination is the emergence of the **radicle**, or primary root, which anchors the seedling to the soil (Bewley and Black, 1994)

## Roots First: Establishing Connection with the Soil

The root system is the plant's first lifeline. Once the radicle emerges, it branches into fine root hairs that greatly increase the absorbing surface area.

## These roots help the seedling:

- absorb water and minerals
- stabilize in the soil
- form early associations with soil microbes

Physiologically, root growth depends on hormones such as auxins and cytokinins, along with sufficient energy from stored reserves. Strong early root development supports better growth later in the plant's life (Taiz, 2015).

## Emergence of the Shoot: Reaching Toward Light

After the root system is established, the shoot begins to push upward. Seedlings follow two main patterns:

- **Epigeal emergence** — cotyledons rise above the soil surface
- **Hypogeal emergence** — cotyledons remain below the soil for protection

As the shoot reaches light, chlorophyll develops and **photosynthesis** begins. This marks a major transition — the young plant shifts from dependence on stored food to self-sustained energy production.



### Plant hormones play a crucial role in this stage:

- **Gibberellins** stimulate stem elongation
- **Auxins** guide directional growth toward light
- **Cytokinins** support cell division and leaf expansion

Together, these signals coordinate growth and orientation in the new environment.

### Physiological Adjustments for Survival

The seedling stage is highly vulnerable. Environmental stresses such as drought, salinity, poor aeration, temperature extremes, or nutrient deficiency can affect survival.

To cope with stress, seedlings activate several physiological mechanisms:

- osmotic adjustment to maintain water balance
- antioxidant activity to protect young tissues
- regulation of growth to conserve energy under stress

Seedlings that successfully adapt during this phase develop better resilience and improved performance in later growth stages (Baskin, C. C. and Baskin, J. M. 2014).

### Why Early Seedling Growth Matters

Seedling emergence and establishment influence:

- plant survival rate
- root architecture and nutrient uptake

- crop stand uniformity
- productivity and yield potential

Strong seedlings form the foundation for healthy plants, sustainable crops, and resilient ecosystems.

### Conclusion

Seedling emergence is not just the start of growth — it is the defining beginning of plant life, where physiology, environment, and survival come together. During this stage, the young plant establishes its roots, begins photosynthesis, and adapts to light, soil, and moisture conditions. The success of these early physiological processes decides whether the seedling can survive, grow, and develop into a strong and productive plant.

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# Bioplastics as an Emerging Alternative to Conventional Plastics

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Plastic has become an integral part of our day-to-day lives, with its applications extending to almost every aspect of human activity. Its widespread use has made it difficult to imagine a world without plastic because of its versatility, durability, lightweight nature, and low production cost. Although plastics have significantly improved living standards and facilitated technological advancements, their excessive production and indiscriminate disposal have resulted in severe environmental and ecological consequences. Plastic pollution poses a serious threat not only to human health but also to wildlife, aquatic ecosystems, terrestrial habitats, and the overall sustainability of the planet. Therefore, there is an urgent need to develop sustainable solutions to address this growing problem.

## Introduction

The history of plastics happens to be as a result of the development of synthetic polymers. Long before the modern plastics were invented, humans utilized naturally occurring polymeric materials because of their moldable properties or so to say plastic like properties. Plant-derived resins and natural latex were softened by heat and shaped into tools, weapons, adhesives, and other functional materials by ancient civilizations. Among these materials, natural rubber obtained from the rubber tree (*Hevea brasiliensis*), native to the Amazon Basin, emerged as one of the earliest and most versatile natural polymers. As industrialization progressed during the nineteenth century, the commercial importance of natural rubber increased considerably following the successful establishment of rubber plantations in Southeast Asia. The development of vulcanization further enhanced the mechanical strength, elasticity, and durability of rubber, making it suitable for a wide range of industrial applications. In parallel, several other naturally derived polymeric materials, including gutta-percha, cellulose, Parkesine, rayon, and cellophane, were developed and used extensively in electrical insulation, photography, textiles, and packaging. Thus, until the early twentieth century,

most plastic-like materials originated from renewable biological resources. However, the growing industrial demand during the Second World War, together with the disruption of natural rubber supplies, accelerated the search for synthetic alternatives. Consequently, the plastics industry shifted towards petroleum-based feedstocks, with fossil fuels becoming the principal raw material for manufacturing synthetic plastics (Paterson, 2019).

Global plastic production has risen sharply from approximately 2 million tonnes in 1950 to nearly 460 million tonnes in 2019, with packaging accounting for the largest share of consumption. Inadequate disposal and inefficient waste management have resulted in the widespread accumulation of plastic waste in terrestrial and aquatic ecosystems. Over time, environmental weathering fragments plastics into microplastics, which can enter food chains, accumulate in living organisms, and pose risks to both ecosystem and human health through cellular toxicity and the transport of hazardous contaminants (Yang *et al.*, 2024).

The growing impacts of plastic pollution on ecosystems, biodiversity, and human health have intensified the search for sustainable alternatives.



Consequently, researchers worldwide are developing renewable and environmentally friendly materials such as bioplastics to reduce dependence on conventional petroleum-based plastics. Although the concept of bioplastics dates back more than a century, they have gained significant attention in recent years as sustainable alternatives to conventional plastics.

### What Are Bioplastics?

Bioplastics are polymeric materials produced wholly or partially from renewable biological resources, such as starch, cellulose, vegetable oils, sugars, and other forms of biomass. Unlike conventional plastics, which are primarily derived from fossil fuels, bioplastics utilize renewable feedstocks, thereby reducing dependence on non-renewable resources. Bioplastics can be classified into biodegradable and non-biodegradable types based on their chemical structure rather than the source of the raw material. Biodegradable bioplastics are designed to be broken down by naturally occurring microorganisms, such as bacteria and fungi, into simpler substances including carbon dioxide, water, biomass, and, under anaerobic conditions, methane. However, this degradation occurs only under suitable environmental conditions, such as appropriate temperature, moisture, and microbial activity. In contrast, non-biodegradable bioplastics are also produced from renewable biomass but possess chemical structures similar to those of conventional plastics. As a result, they do not readily decompose in the environment and require proper recycling or waste management. Therefore, the term "bioplastic" refers to the origin of the raw material, its biodegradability, or both. Consequently, not all bioplastics are biodegradable, and not all biodegradable plastics are derived from renewable biological resources.

Although bioplastics are gaining increasing attention as sustainable alternatives to conventional plastics, their global production remains relatively low. In 2020, approximately 2.1 million tonnes of bioplastics were produced, compared to 367 million

tonnes of conventional plastics. Their widespread adoption is currently constrained by the high cost of renewable feedstocks, complex microbial and biochemical production processes, and additional purification steps required during manufacturing. Nevertheless, advances in biotechnology have enabled the production of bio-based conventional plastics, such as bio-polyethylene (Bio-PE), bio-polypropylene (Bio-PP), and bio-polyethylene terephthalate (Bio-PET), which are derived wholly or partly from renewable biomass while maintaining properties comparable to those of petroleum-based plastics. These developments demonstrate the growing potential of renewable biomass to support a more sustainable and circular plastics industry (Fredri & Dorigato, 2021; PlasticsEurope, 2021; Mujtaba et al., 2023).

### 3. Are Bioplastics Better for the Environment?

Bioplastics have become a subject of considerable debate regarding their overall environmental impact. Although they are widely recognized as promising alternatives to conventional petroleum-based plastics, they are not without limitations and continue to face several environmental and practical challenges.

The persistence of plastics in the environment is largely governed by their physical and chemical properties, including molecular mobility, crystal structure, molecular weight, and the presence of functional groups. Plastics with high molecular weight, a high degree of crystallinity, greater hydrophobicity resulting from their linear polymeric carbon-chain backbone, and low water solubility generally exhibit poor biodegradability. These characteristics are responsible for the persistence of conventional petroleum-based plastics, such as polyethylene (PE) and polypropylene (PP), in the environment (Akindoyo et al., 2021).

Biodegradable bioplastics generally undergo degradation through the gradual breakdown of their



long polymer chains into smaller molecules, such as oligomers, dimers, and monomers, under the influence of environmental factors including moisture, sunlight, and temperature. These smaller molecules can then pass through the semipermeable membranes of microorganisms, where they serve as substrates for microbial metabolism (Shah et al., 2008).

Although biodegradable bioplastics can degrade efficiently under controlled conditions, their decomposition is often much slower in natural environments. Their biodegradability depends not only on the properties of the material but also on environmental factors such as temperature, moisture, and microbial activity. In natural environments or landfills, where favourable composting conditions are often absent, the degradation of compostable bioplastics is considerably slower, increasing the likelihood of environmental accumulation. Consequently, without suitable disposal and composting facilities, some bioplastics may ultimately persist in the environment in a manner similar to conventional fossil fuel-based plastics (Ali et al., 2023).

Overall, bioplastics offer significant environmental advantages by reducing dependence on fossil resources and providing the potential for biodegradation. However, they are not a universal solution to plastic pollution. Their environmental performance depends on the type of bioplastic, appropriate disposal methods, and the availability of suitable composting or waste management infrastructure. Therefore, maximizing the benefits of bioplastics requires not only sustainable material development but also effective waste management practices and increased public awareness.

#### 4. Why Lignocellulosic Biomass?

Lignocellulosic biomass refers to non-edible plant materials that form the structural framework of plants. It is primarily composed of three major

components cellulose, hemicellulose, and lignin along with small amounts of extractives. Unlike food-based feedstocks, lignocellulosic biomass does not compete directly with the human food supply, making it an attractive and sustainable raw material for producing bio-based products, including bioplastics.

Based on its source, lignocellulosic biomass can be broadly classified into agricultural residues, forestry biomass, and dedicated energy crops. Agricultural residues include rice straw, wheat straw, corn stover, cotton stalks, rice husks, oat husks etc which are generated in large quantities after harvesting. Forestry biomass consists of wood chips, sawdust, bark, wood logs, and other residues produced during timber harvesting and wood processing. Dedicated energy crops, such as switchgrass, elephant grass, poplar, willow, timothy grass etc are cultivated specifically for the production of renewable energy and bio-based materials.

Every year, enormous quantities of agricultural and forestry residues are generated worldwide, much of which is underutilized or disposed of through open-field burning or landfilling. These practices not only waste valuable biomass resources but also contribute to greenhouse gas emissions and environmental pollution. Converting these abundant residues into value-added products such as bioplastics offers an effective way to utilize waste while reducing environmental impacts.

Lignocellulosic biomass obtained from agricultural and forestry residues has emerged as a promising alternative to petroleum-based resources. It has significant potential to replace conventional plastics and other petrochemical-derived polymeric materials. The use of this renewable biomass reduces dependence on fossil fuels, contributes to climate change mitigation by lowering carbon emissions, and supports the development of a sustainable circular bioeconomy



Depending on the manufacturing process, lignocellulosic biomass can be used either directly as a reinforcing material in bioplastic formulations or indirectly after conversion into valuable intermediates such as cellulose, sugars, or other bio-based polymers. Moreover, waste generated from agricultural, forestry, and wood-processing industries can also serve as an inexpensive and renewable feedstock, transforming low-value residues into high-value sustainable materials. This approach not only adds value to agricultural and forestry waste but also promotes resource efficiency and supports the transition towards greener and more sustainable plastic production.

## 6. Challenges and the Road Ahead

Although bioplastics have emerged as promising alternatives to conventional plastics, several challenges continue to limit their widespread adoption. At present, bioplastics can replace fossil fuel-based plastics only in selected applications. For instance, materials such as polylactic acid (PLA) are increasingly being used in packaging as alternatives to conventional plastics like polyethylene terephthalate (PET), low-density polyethylene (LDPE), and high-density polyethylene (HDPE). However, complete replacement is still difficult due to the higher production costs of bioplastics and certain limitations in their chemical, mechanical, and processing properties (Mujtaba et al., 2023).

Many bioplastics exhibit lower mechanical strength, reduced flexibility, brittleness, poor gas barrier properties, or limited resistance to moisture compared with conventional plastics. Starch, one of the most abundant, inexpensive, and widely available natural polymers, is an excellent example. Despite its sustainability and low cost, its poor water resistance and relatively weak mechanical properties restrict its direct use in many commercial applications. As a result, starch is often blended with other biodegradable polymers or modified to improve its performance.

Despite these challenges, rapid advances in biotechnology, materials science, and biomass processing are steadily improving the performance and affordability of bioplastics. Continued research on lignocellulosic biomass, green manufacturing technologies, and efficient recycling and composting systems is expected to expand their applications in the future. With supportive policies, technological innovations, and responsible waste management, bioplastics have the potential to play a significant role in reducing plastic pollution and building a more sustainable circular bioeconomy.

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# Role of Cloud Computing Technology in Agriculture Fields

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Use of Cloud computing technology in agricultural areas has greater chance in the overall development of India. An effective implementation of cloud computing is encouraging in agricultural sector. Cloud Computing is emerging today as a commercial infrastructure that eliminates the need for maintaining expensive computing hardware, software, Information technology, staff, infrastructure, recourses and their maintenance. Cloud computing is a network-based environment that focuses on sharing computations, Cloud computing networks access to a shared pool of configurable networks, servers, storage, service, applications & other important computing resources. In modern era of cloud computing technology very helpful for centralized the allagricultural related data bank (Soil-related, weather, Research, Crop, Farmers, Agriculture marketing, fertilizers and pesticide information) in the cloud. In this paper, also discuss Computing model, characteristics, deployment model, cloud service model, cloud benefits and challenge of cloud computing in agriculture field. Keywords: Cloud computing, Community model, Hybrid model, Public model, Private model, Agriculture, IaaS, Paas & SaaS

## 1.1 Introductions

Cloud computing is the provision of computer or IT infrastructure through the Internet. That is the provisioning of shared resources, software, applications and services over the internet to meet the elastic demand of the customer with minimum effort or interaction with the service provider. India is one of the largest producers of foods, grains and other products, but still agriculture and its production process are decentralized, unsophisticated and outdated methods being followed by the farmers, together with several constraints of the farmers and modernization is very slow. This results in an obvious gap between the supply and demand chains of the agricultural products. This will have a negative impact on the farmer's economic conditions as well the national income of the country. This bottleneck can be eliminated with the implementation of Cloud Computing facility in agricultural field. The centralized location has to be set up to store all the relevant data. It can include various, Separate databases Soil-related, weather-related, Research, Crop and Farmers-related data can all be stored at a

single location, and data availability can be achieved. This data can be accessed by the end-users such as farmers, experts, consultants, researchers etc easily any time from any location through the devices that are connected to the cloud system.

## 1.2 Computing Models

### 1.2.1 Desktop Computing

This type of computing used in single PC Computing.

This types of computing facility applicable for personal, professional (Engineer, artist, authors, doctors, programmers) office and publishing house.

### 1.2.2 Client server computing

Client server computing is a system that performs both the functions of client and server to promote the sharing of information between them. A Client is any process that requests specific services from the server process. A Server is a process that provides requested services for the Client. it allows many users to have access to the same database at the same time, and the database will store much information. Various types



of server used in Clint service computing such as mail server, file server, fax server, database server, web server. Example of client server System, File transfer: This is the transmission of files between the client and server. It also allows storing of files on the server. Files such as movies, images, music can be stored.

**1.2.3 Cluster computing** In cluster computing, a group of similar computers is hooked up locally to operate as a single compute. This facility utilized for load balance of servers. Main advantages of this computer technology is distributed the load of server among the each servers of computer.

**1.2.4 Grid Computing** Grid computing is the collection computers resources from multiple locations to reach a common goal. Benefits of grid computing are Increase access to data and collaboration, join data and distribute it globally, Support large multi-disciplinary collaboration, Workload balance, data security etc. Main characteristics of grid computing listed in the below:

- Grid coordinates Resources that are not subjected to centralized control.
- Grid use standard, open, general-purpose protocols and interfaces.
- Grid deliver high quality of Service.

**1.2.5 Cloud Computing** Cloud computing is the combination of cluster and grid computing. The IT environment evolved from mainframes to client servers, the Internet, virtualization and cloud computing. Cloud computing provides a shared pool of configurable IT resources (e.g. processing, network, software, information and storage) on demand, as a scalable and elastic service, through a networked infrastructure, on a measured (pay-per-use or subscription) basis, which needs minimal management effort, is based on service level agreements between the service provider and consumers, and often utilizes virtualization resources.

## 2.0 CHARACTERISTICS OF CLOUD COMPUTING

- **On-demand self-service:** A consumer can unilaterally provision computing capabilities, such as server time and network storage, as needed automatically without requiring human interaction with each service provider.
- **Broad network access:** Capabilities are available over the network & accessed through standard mechanisms that promote use by heterogeneous thin or thick client platforms (e.g., mobile phones, tablets, laptops, and workstations).
- **Rapid elasticity:** Cloud services can be rapidly and elastically provisioned, in some cases automatically, to quickly scale out and rapidly released to quickly scale in. To the consumer, the capabilities available for provisioning often appear to be unlimited and can be purchased in any quantity at any time.
- **Measured service:** Pay per use-capabilities is charged using a metered, fee-for-service, or advertising based billing model to promote optimization of resource use. Examples are measuring the storage, bandwidth, & computing resources consumed and charging for the number of active user accounts per month.
- **Resource pooling:** The provider is computing resources are pooled to serve multiple consumers using a multi-tenant model, with different physical and virtual resources dynamically assigned and reassigned according to consumer demand. There is a sense of location independence in that the customer generally has no control or knowledge over the exact location of the provided resources but may be able to specify location at a higher level of virtuality (e.g., country, state, or data center). Examples of resources include storage, processing, memory, network bandwidth, and virtual machines.



### 3.0 DEPLOYMENT MODEL OF CLOUD COMPUTING

#### 3.1 Public cloud

The cloud infrastructure applications, storage, and other resources are made available to the public for free or on pay-per-use model. It is owned by an organization selling cloud services. Example: Amazon, Google Apps, Windows Azure etc. Some Important point for Public Cloud

- Entirely hosted by External Providers
- Almost any customer can pay for resource on the cloud
- Support is handling by the provider.

**3.2 Community cloud** The cloud shares infrastructure for specific community with common concerns (security, compliance, jurisdiction etc), whether managed internally or by a third party and hosted internally or externally.

**3.3 Hybrid cloud** The cloud infrastructure is a composition of two or more clouds (private, community, or public) that re-main unique entities but are bound together by standardized or proprietary technology that enables data and application portability.

**3.4 Private cloud** The cloud infrastructure is operated solely for a single organization. It may be owned, managed and operated by the organization or a third party, and may exist on-premises or off-premises

### 4. MODEL OF CLOUD COMPUTING

**4.1 SaaS (Software as a service) model:** Through this service delivery, model end users use the software application services directly over network according to on-demand basis. In this type, service only required administrator & cloud consultants. Example salesforce, drop box and Google applications such as Email, Google drive, talk etc.

**4.2 PaaS (Platform as a service) model:** In the PaaS model, cloud providers deliver a computing platform, typically including operating system, programming language execution environment, database, and web server. This type service only software developer required for deployment of software, Example Google application engine, window Azure, force.com etc.

**4.3 Infrastructure as a service (IaaS):** In an IaaS model, resources can easily be scaled up, depending upon the demand from the user, services being charged in a pay-per use model. Network administrator & programmer required for IaaS services, Example Amazon web service, IBM, HP etc.

### 5.0 ROLE OF CLOUD COMPUTING IN AGRICULTURE FIELD (RURAL & HILLS)

- Agriculture information data bank (crop, weather, soil, growth progress, farmer data & expert consultation).
- Store all the agriculture-related information in a centralized cloud, which will be available to all the users at anytime, anywhere
- Management of all data related to land, location, area; soil and land characteristics through centralized decision support systems
- High integration & sharing of agricultural information
- It can eliminate the farmer's limitations of technical knowledge & resources
- Providing agricultural technology service & science
- Improvement of the agricultural products marketing
- Efficient use of agricultural resources
- Promote the circulation of agricultural product and service in wider level.



## 6. BENEFITS OF CLOUD COMPUTING IN AGRICULTURE

- Data Readiness any time & any where
- Local and global communication
- Improve economic condition of the Nation
- Enhanced the GDP of the nation
- Ensure food security level
- Motivation of farmers and researchers
- Reduction of technical issue
- Rural-Urban movement
- Data availability at any time and at any location without delay
- Improve market price of Food, seeds, other product

## 7. CHALLENGE OF CLOUD COMPUTING IN AGRICULTURE

- Maintenance & Supervision by third party, So data security is less
- Indirect administrator accountability
- Farmer is unknown for cloud computing technology
- Less physical control
- Attraction to hackers

- Need on the network connectivity
- Requires a constant Internet connection
- Platform facility is not easily available for farmers
- Farmers training necessary for this technology
- Does not work well with low-speed connections
- it runs the risk of security 8.

## CONCLUSION

This prominent technique may deliver the agriculture-based knowledge along with management of natural resources and knowledge directly to the consumers not only in a small region like in nonstop marketing or shops but also in a wider region. This will change the whole supply chain, which is mainly in the hand of large companies, now, but can change to a more direct, shorter chain between producers and consumers. Cloud computing technology, applicable for the improvement of agriculture growth, food, grain, product, economic condition, Ensure food safety, GDP of the nation & circulate information related to agriculture etc.

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## Sweet Flag (*Acorus calamus* L.): Cultivation Practices and Therapeutic Significance

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Sweet flag (*Acorus calamus* L.) is an important aromatic crop belonging to the family Acoraceae. It is widely valued for its aromatic rhizomes which are rich in essential oil containing asarone and  $\beta$ -asarone. The plant has been used for centuries in Ayurveda, Siddha and other traditional systems of medicine for improving memory, digestion, respiratory health and nervous disorders. It thrives in marshy, moist environments and is cultivated mainly through rhizome propagation. For successful cultivation in fertile soils rich in organic matter, regular irrigation and balanced nutrient management are essential. Timely weeding, proper field maintenance and effective control of pests such as slugs and mealybugs along with diseases like leaf spot help achieve higher yields. Harvesting is carried out 6–8 months after planting when the leaves begin to dry producing good-quality rhizomes with valuable essential oil. Owing to its medicinal, aromatic and commercial importance sweet flag continues to be a promising crop for herbal medicine and essential oil production.

### Introductions

Sweet flag (*Acorus calamus* L.) is a herb belonging to the family Acoraceae. It is also known as calamus, flagroot, sweet cane, sweet grass, sweet root, Vacha and Vasambu (Tamil). It is sterile and triploid. Sweet flag is a native of India and Asia and has now been introduced across Europe, Australia, New Guinea, South Africa, Reunion and North America. It is a perennial plant growing wild on edges of swamps and on banks of rivers and ponds in North America, Europe and Asia. Commercial production of sweet flag is done throughout tropical and subtropical countries like Russia, Central Europe, Romania, India and Japan. This plant is available both under wild and cultivated conditions in India. In the marshy areas of Kashmir and Sirmur in Manipur and Naga Hills, it is abundant. It is cultivated in one district Koratagere in Karnataka State, India. Rhizomes, roots and leaves yield essential oil.

Traditionally the fragrant leaves and stronger-scented rhizomes have been used medicinally and to create fragrances. The dried and powdered rhizome

has also been used as a substitute for nutmeg, ginger and cinnamon. The important constituents of the Indian oil are asarone and  $\beta$ -asarone. Steam distillation can be used to separate its volatile yellowish-brown oil, which has a peculiar and pleasant, somewhat sweet smell. The dried root (rhizome) has long been employed in medicinal preparations and for flavoring liquors. The plant essential oil, which includes the glucosidic bitter component "ACORIN," imparts it an aromatic quality. Very long history of medicinal use in Chinese, Nepal and Indian herbal traditions. The leaves, stems, and roots are used in various Siddha and Ayurvedic medicines. It is capable of improving memory and intellect. It has been used as an aromatic stimulant and mild tonic, carminative, diaphoretic, expectorant, hypotensive and sedative medicinal plant. The sweet flag is capable of improving memory power and intellect. For infants used against colic pain. It is used in vitiated conditions of hoarseness, nephropathy, cough bronchitis, inflammations, gout, depression and other mental disorders, tumours, dysentery, skin diseases. It is





reportedly useful in improving digestion, clearing speech and dysentery.

### Botany

*A. calamus* is a rhizomatous, branched, semi-aquatic, creeping herb, usually perennial, rarely biennial and a monocot plant. Light brown to pinkish brown, rhizomes 1.2-2.5 cm thick are cylindrical, compressed, spongy and sometimes up to 2 m long. Leaves are bright green, measuring 0.9 to 1.5 m in length and 1.7-3.5 cm in width. A scape or flower stem arises from the axils of outer leaves. From one side, near the middle of its length, projecting upwards at an angle from stem, it sends out a solid, cylindrical, blunt spike or spadix, tapering at each end. Somewhat curved and densely crowded with very small greenish-yellow flowers. Each tiny flower contains 6 stamens enclosed in a perianth with 6 divisions and surrounding a three celled, oblong ovary with a sessile stigma. Flowers are sweet scented and so formed that cross pollination is ensured. The fruit is a berry, yellow-green in colour, angular and 1-3 seeded.



### Species

1. ***Acorus calamus***: Common sweet flag. It is sterile triploid ( $3n = 36$ ). It is native to Europe, temperate India and the Himalayas and southern Asia and widely cultivated and naturalized elsewhere. It is found growing wild or cultivated throughout India and Sri Lanka, ascending to 1800 m in the Himalayas.
  - *Acorus calamus* var. *angustatus*
  - *Acorus calamus* var. *calamus*

2. ***Acorus gramineus***: It is also known as Japanese sweet flag or grassy-leaved sweet flag. It is fertile diploid ( $2n = 18$ ). The midrib of the leaf is missing here. The inside of the rhizome will be spongeline white while the outside will be brown. Similar to *A. calamus* it is utilized for therapeutic purposes.

### Varieties

**CIM-Balya**: Released from CSIR-CIMAP in the year 2010. Major Constituents of Variety - Beta-sarone. A high rhizome and oil yielding variety.

### Soil and climate

*Acorus* is a hardy plant growing from tropical to subtropical climates under 10-38°C temperature. It needs a good and well-distributed rainfall throughout year 70-250 cm. It needs ample sunlight during growth period as well as after harvest for drying rhizomes. It may be cultivated in any good but fairly moist soil. Sweet flag thrives best in marshy and moist places under variable climates. The plant is grown in clayey loams and light alluvial soils of the riverbanks. It is typically planted in regions suitable for rice cultivation. It thrives on light alluvial soils along riverbanks and clayey soils. The field is well irrigated and set up just as for rice. Ploughed twice, then thoroughly watered and ploughed again.



### Propagation

Sprouted rhizome is used for replanting and propagation. Pieces are used for planting and pressed into mud to a depth of about 5cm at a spacing of 30x30cm. Approximately 40,000 rhizome pieces are required per acre.

Considering that there should be ample sunshine available at harvest time to dry the rhizomes, the crop



can be sown practically any time of the year. Spring (March–April) is the most ideal time to plant.

### Manures and Fertilizers

Before planting the field should be enriched with about 10–12 t/ha of green manure and 15 t/ha of well-decomposed compost to improve soil fertility and organic matter content. In addition a basal application of 100 kg ammonium sulphate, 300 kg superphosphate and 100 kg muriate of potash per hectare is recommended. Alternatively, a fertilizer dose of 125:125:125 kg N:P<sub>2</sub>O<sub>5</sub>:K<sub>2</sub>O per hectare may be supplied in three equal split applications during the crop growth period to ensure efficient nutrient uptake and better crop performance.

### Irrigation

The crop should be irrigated regularly to maintain adequate soil moisture throughout its growth. During the initial stages approximately 5 cm of standing water is maintained in the field. As the plants develop and their water requirement increases the water level is gradually raised to about 10 cm to support healthy growth and optimum development. Irrigation may be avoided during rainy season, however, if there is prolonged dry spell it may be irrigated at an interval of 2-3 days.

### After care

Timely weeding and hoeing to control the spread of weeds and to obtain a good yield are essential to minimize competition for nutrients, water and light. After each weeding operation the plants are gently pressed or earthed up into the soil to provide better anchorage, promote healthy growth and prevent lodging.

### Harvesting

The lower leaves turn yellow and dry, indicating their maturity. The plant starts yielding by 6-8 months after sowing. The carefully collecting rhizomes after digging soil. The field is allowed to dry partially so

that sufficient moisture is retained to facilitate the necessary deep digging. Rhizome yield is about 10 tonnes/ha. Rhizomes are washed thoroughly to remove adhering soil, all fibrous roots are removed and then they are cut into pieces of 5-7.5 cm in length. The yield of dry rhizomes is about 3 to 4 t/acre. Dried rhizomes contain about 2-3% oil.



### Plant protection

#### Pest and their management:

**Slug damage:** It is the damage caused by the slug on the leaves of the plant. They feed themselves on fresh leaves of plants. Application of metaldehyde or iron phosphate is used to get rid of slugs.

**Mealy bugs:** Caused by *Lepidocephalus* and *Pseudococcus*. The leaves start yellowing and withering. Application of Methyl parathion@10ml or Quinalphos@20ml in 10L of water is done on roots and shoots of the plant.

#### Diseases and their management:

**Leaf spot:** The fungal discolored spots occur on the leaves of the plant. Application of Captan @10g and Chlorpyrifos @20ml/10L should help to control the leaf spot.

### Conclusion

Sweet flag is a perennial medicinal and aromatic herb cultivated primarily for its rhizomes which are rich in essential oils and bioactive compounds. It grows best in warm, humid climates with moist or marshy soils and is propagated through rhizome cuttings. The plant is widely used in Ayurvedic and Siddha medicine for its digestive, neurological and therapeutic properties. Proper crop management including balanced nutrition, regular irrigation, weed control and timely plant protection is essential for achieving higher rhizome yield and quality. Owing to



its medicinal importance, essential oil content and commercial value, sweet flag is an important crop for the herbal and pharmaceutical industries.

<https://www.apnikheti.com/en/pn/agriculture/horticulture/medicinal-plants/sweet-flag>

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# Artificial Intelligence (AI) in Horticulture: Transforming Modern Crop Production

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Artificial Intelligence (AI) has emerged as one of the most promising technologies for improving productivity, sustainability, and profitability in horticulture. By integrating machine learning, computer vision, robotics, drones, sensors, and the Internet of Things (IoT), AI enables precise crop monitoring, early disease detection, smart irrigation, yield prediction, and automated harvesting. These technologies help optimize the use of water, fertilizers, pesticides, and labor while improving the quality and quantity of horticultural produce. AI-driven decision support systems also assist growers in making timely and data-based management decisions. Despite challenges such as high implementation costs, limited technical knowledge, and inadequate digital infrastructure, AI is expected to play a crucial role in the future of sustainable horticulture. This article discusses the concept of AI, its major applications, benefits, limitations, and future prospects in horticultural production.

## Introductions

Horticulture is one of the most dynamic sectors of agriculture, encompassing the cultivation of fruits, vegetables, flowers, plantation crops, medicinal plants, and spices. Increasing demand for high-quality produce, climate variability, shrinking agricultural land, and labor shortages have encouraged the adoption of advanced technologies in horticultural farming.

Artificial Intelligence (AI) is revolutionizing the way horticultural crops are produced and managed. AI enables computers and machines to analyze large volumes of data, recognize patterns, and make intelligent decisions with minimal human intervention. Combined with sensors, drones, satellites, and automated equipment, AI is making horticultural production more efficient, precise, and environmentally sustainable.

## What is Artificial Intelligence?

Artificial Intelligence refers to the capability of computer systems to perform tasks that normally

require human intelligence, including learning, reasoning, problem-solving, and decision-making.

The major components of AI used in horticulture include:

- Machine Learning (ML)
- Deep Learning (DL)
- Computer Vision
- Internet of Things (IoT)
- Robotics
- Big Data Analytics

Together, these technologies support precision horticulture by providing real-time monitoring and intelligent crop management.

## Applications of AI in Horticulture

### 1. Early Detection of Diseases and Pests:-

AI-powered image recognition systems can identify plant diseases and insect infestations at an early stage by analyzing photographs of leaves, stems, and fruits. Early diagnosis minimizes crop losses and reduces unnecessary pesticide applications.



## 2. Smart Irrigation Management:-

AI integrates weather forecasts, soil moisture data, and crop water requirements to determine the optimum irrigation schedule. This approach improves water-use efficiency and prevents both over-irrigation and water stress.

## 3. Nutrient Management:-

Sensors and AI algorithms continuously monitor crop nutrient status and recommend balanced fertilizer application based on crop demand, thereby improving nutrient-use efficiency and reducing production costs.

## 4. Yield Prediction:-

Machine learning models analyze historical production records, weather conditions, soil characteristics, and crop growth patterns to estimate expected yields. Accurate yield prediction helps farmers plan harvesting, storage, transportation, and marketing activities.

## 5. Fruit Quality Assessment and Grading:-

Computer vision technology automatically evaluates fruit size, color, shape, surface defects, and maturity. AI-based grading systems improve consistency, reduce post-harvest losses, and enhance export quality.

## 6. AI-Based Drones and Robotics:-

Autonomous drones equipped with AI capture aerial images for crop health monitoring, nutrient deficiency detection, and precision pesticide spraying. Robotic systems are increasingly being used for harvesting, pruning, and weed management in commercial orchards and vegetable farms.

## 7. Greenhouse and Protected Cultivation:-

AI controls environmental factors such as temperature, humidity, light intensity, carbon dioxide concentration, and ventilation in greenhouses.

Automated climate management creates ideal growing conditions, resulting in higher productivity and superior crop quality.

## 8. Weed Detection and Precision Spraying:-

Computer vision algorithms distinguish weeds from crop plants and enable site-specific herbicide application. This reduces chemical usage, production costs, and environmental pollution.

## Advantages of AI in Horticulture:-

- Enhances crop productivity and quality.
- Reduces water, fertilizer, and pesticide consumption.
- Improves early detection of diseases and pests.
- Minimizes labor requirements and operational costs.
- Supports real-time crop monitoring and management.
- Increases resource-use efficiency.
- Reduces post-harvest losses.
- Promotes environmentally sustainable farming.
- Assists farmers in making data-driven decisions.

## Challenges in AI Adoption:-

Despite its significant advantages, several challenges limit the widespread adoption of AI in horticulture:

- High initial investment in AI equipment and software.
- Limited digital infrastructure in rural regions.
- Inadequate technical knowledge among farmers.
- Requirement for high-quality and large datasets.
- Maintenance and calibration of advanced devices.





- Limited affordability for small and marginal farmers.

### Future Prospects

Artificial Intelligence is expected to become an integral component of future horticultural production systems. Advancements in autonomous robots, intelligent greenhouse management, digital twins, AI-powered advisory platforms, and cloud-based farm management systems will further improve production efficiency. Integration of AI with remote sensing, satellite imagery, blockchain technology, and climate forecasting models will strengthen sustainable horticultural development. As technology becomes more affordable and accessible, AI adoption is likely to increase rapidly in developing countries, including India.

### Conclusion

Artificial Intelligence has the potential to redefine horticultural production by improving efficiency, sustainability, and profitability. AI-based technologies enable precision crop management, reduce production costs, conserve natural resources, and improve the quality of horticultural produce. Although challenges related to cost, infrastructure, and technical expertise remain, continuous technological advancements and supportive government initiatives are expected to accelerate AI adoption. The future of horticulture will increasingly depend on intelligent technologies that help farmers produce more with fewer resources while ensuring environmental sustainability.

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# Napier Grass: A Green Lifeline for the Coastal Saline Zone of West Bengal

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The coastal saline zone of West Bengal faces severe constraints to fodder production due to soil salinity, tidal inundation, recurrent cyclones, and increasing climate variability. These challenges necessitate the adoption of climate-resilient forage crops to sustain livestock production. Napier grass (*Pennisetum purpureum*) has emerged as a promising perennial forage because of its high biomass productivity, rapid regeneration, efficient resource utilization, and moderate tolerance to salinity and other abiotic stresses. This article highlights the botanical and physiological characteristics, agronomic importance, production technologies, improved cultivars, nutritional value, and livestock benefits of Napier grass, with particular emphasis on its suitability for the coastal saline zone of West Bengal. The article also discusses the major constraints affecting its cultivation and outlines future research priorities for developing sustainable fodder production systems. Adoption of improved cultivars, scientific crop management, and climate-smart production practices can significantly enhance fodder availability, livestock productivity, and the resilience of coastal farming systems.

## Introductions

The coastal saline zone (CSZ) of West Bengal is characterized by saline soils, tidal inundation, recurrent cyclones, and increasing climatic variability, all of which severely constrain agricultural productivity and limit year-round availability of quality fodder. These challenges are further exacerbated by rising soil salinity and freshwater scarcity, making the development of climate-resilient forage production systems a priority for sustaining livestock-based farming in the region (Dwivedi *et al.*, 2023).

Napier grass (*Pennisetum purpureum*), a perennial C<sub>4</sub> forage crop species, is recognized for its exceptional biomass productivity, rapid regrowth after harvesting, high resource-use efficiency, and adaptability to a wide range of tropical environments. Its vigorous growth, extensive root system, and moderate tolerance to salinity make it a promising candidate for fodder production in salt-affected

agroecosystems (Islam *et al.*, 2024). Beyond providing a continuous supply of nutritious green fodder, Napier grass contributes to improved soil cover, reduced erosion, and enhanced resilience of integrated crop-livestock systems. Therefore, its strategic promotion in the coastal saline zone of West Bengal could play a pivotal role in strengthening fodder security and supporting climate-smart livestock production. This article examines the agronomic potential, production constraints, and future prospects of Napier grass in this unique agroecological region.

## Coastal Saline Zone of West Bengal: Challenges for Fodder Production:

The Coastal Saline Zone (CSZ) of West Bengal, comprising the Sundarbans and adjoining coastal areas, is characterized by saline soils, tidal inundation, shallow saline groundwater, recurrent cyclones, and erratic rainfall. These environmental constraints limit agricultural productivity and



substantially reduce the year-round availability of quality fodder for livestock. Soil salinity causes osmotic stress, ionic toxicity (primarily  $\text{Na}^+$  and  $\text{Cl}^-$ ), and nutrient imbalance, resulting in poor crop establishment and reduced biomass production. Climate change has further aggravated these problems through sea-level rise and increased saline water intrusion, making the development of climate-resilient fodder production systems essential for sustaining mixed crop–livestock farming in coastal ecosystems (Islam *et al.*, 2023).

### **Napier Grass: Botany, Physiology, and Agronomic Importance:**

Napier grass (*Pennisetum purpureum*) is a perennial  $\text{C}_4$  forage grass belonging to the family Poaceae. Native to tropical Africa, it is widely cultivated across tropical and subtropical regions because of its high biomass production, vigorous growth, and adaptability to diverse agroecological conditions. The crop is propagated mainly through stem cuttings and remains productive for several years under proper management.

As a  $\text{C}_4$  species, Napier grass exhibits high photosynthetic efficiency, superior water-use efficiency, and efficient utilization of solar radiation, resulting in rapid biomass accumulation. Its deep and extensive root system also imparts moderate tolerance to drought and salinity, making it suitable for cultivation in climate-stressed environments, including coastal saline areas (Mukhtar *et al.*, 2022).

Agronomically, Napier grass is valued for its rapid regrowth, excellent ratooning ability, multiple harvests, and high forage yield. These characteristics ensure a continuous supply of nutritious green fodder while contributing to soil conservation and the sustainability of crop–livestock farming systems, making it a promising forage crop for the coastal saline zone of West Bengal (Negawo *et al.*, 2017).

### **Salinity Tolerance and Climate Resilience:**

Napier grass (*Pennisetum purpureum*) exhibits moderate tolerance to salinity and can sustain growth under mild to moderate salt stress through physiological adaptations such as efficient osmotic adjustment, an extensive root system, and the  $\text{C}_4$  photosynthetic pathway, which improve water-use efficiency. However, higher salinity levels reduce plant growth, biomass yield, and forage quality, including crude protein content. The adoption of salt-tolerant cultivars, integrated nutrient management, and appropriate soil reclamation practices can mitigate these adverse effects and enhance forage productivity. Therefore, Napier grass is considered a promising climate-resilient forage crop for improving fodder security in the coastal saline zone (CSZ) of West Bengal (Alam *et al.*, 2017).

### **Production Technologies and Recommended Cultivars:**

Successful cultivation of Napier grass relies on improved cultivars and scientifically optimized agronomic practices. The crop is propagated vegetatively using healthy stem cuttings with two to three nodes and is preferably established during the monsoon or under irrigated conditions. Application of 10–15 t ha<sup>-1</sup> of farmyard manure, balanced NPK fertilization, timely irrigation, effective weed control, and harvesting at 45–60 day intervals promote vigorous growth, high biomass production, superior forage quality, and sustained ratooning. Appropriate spacing (60–90 × 60–90 cm) further enhances tillering and ensures year-round fodder production under tropical conditions.

Several improved Napier and Bajra–Napier hybrid cultivars have been developed in India for enhanced forage production. Cultivars such as CO-3, CO-4, CO-5, DHN-6, IGFRI-6, and Swetika-1 are characterized by high biomass yield, rapid regeneration, superior tillering, and improved nutritive value. In coastal saline regions, cultivar



selection should be based on local agroecological conditions, salinity levels, and water availability. Ongoing breeding programmes at ICAR-Indian Grassland and Fodder Research Institute (IGFRI) continue to develop high-yielding, stress-tolerant hybrids with enhanced forage quality and wider adaptability for sustainable climate-resilient livestock production. (ICAR-IGFRI, 2025).

### Nutritional Value and Livestock Benefits:

Napier grass is a nutritious forage rich in carbohydrates and essential minerals, including calcium, phosphorus, potassium, and magnesium, which support animal growth, milk production, and reproductive performance. Its high palatability and digestibility improve feed intake and nutrient utilization, while its suitability for silage and hay production ensures year-round fodder availability (FAO, 2011).

Regular feeding of Napier grass enhances milk yield, body weight gain, and feed efficiency. When integrated with legumes or concentrate feeds, it provides a balanced diet, improves livestock productivity, and reduces feed costs, making it an ideal forage for sustainable and climate-resilient livestock production in the coastal saline zone of West Bengal.

**Table 1. Typical nutritional composition of Napier grass harvested at 45-60 days**

| Parameter                        | Typical range |
|----------------------------------|---------------|
| Dry matter (%)                   | 18-25         |
| Crude protein (%)                | 8-16          |
| Crude fiber (%)                  | 25-35         |
| Neutral detergent fiber (NDF, %) | 55-70         |

|                                               |           |
|-----------------------------------------------|-----------|
| (%)                                           |           |
| Acid detergent fiber (ADF, %)                 | 30-45     |
| Total digestible nutrients (TDN, %)           | 55-65     |
| Metabolizable energy (MJ kg <sup>-1</sup> DM) | 8.0-10.5  |
| Calcium (%)                                   | 0.30-0.60 |
| Phosphorus (%)                                | 0.20-0.35 |

\*Values represent typical ranges for Napier grass harvested at 45–60 days. Nutrient composition varies depending on cultivar, maturity stage, fertilization, climate, and management practices (McDonald *et al.*, 2022; FAO, 2018).

### Challenges and Future Directions for Sustainable Napier Grass Production:

The sustainable cultivation of Napier grass in the coastal saline zone of West Bengal is constrained by increasing soil salinity, periodic waterlogging, cyclonic disturbances, declining soil fertility, and shortages of quality planting material. These challenges reduce forage productivity and limit the adoption of improved fodder production technologies by smallholder farmers (ICAR-IGFRI, 2023).

Future research should focus on developing salt-tolerant and high-yielding Napier cultivars, improving nutrient and water management strategies, and integrating biofertilizers and conservation practices to enhance productivity under saline environments. Greater emphasis should also be placed on cultivar evaluation under coastal conditions, silage production, and climate-smart crop-livestock integration to ensure sustainable fodder supply and strengthen livestock-based livelihoods (FAO, 2018).



### Success Stories of Farmers Cultivating Napier Grass in Coastal Saline Zone of West Bengal:

| Farmer & Location                                                     | Situation & Intervention                                                                                                                                       | Success Achieved                                                                                                          | Citation                      |
|-----------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------|-------------------------------|
| Sri Pradip Kumar Jana, Contai, Purba Medinipur, West Bengal           | A paddy-based farmer adopted hybrid Napier grass cultivation to overcome seasonal fodder scarcity through improved planting and nutrient management practices. | Regular green fodder availability, reduced fodder purchase cost, and improved livestock feeding management were achieved. | (Saha <i>et al.</i> , 2024)   |
| Sri Subhas Chandra Das, Patharpratima, South 24 Parganas, West Bengal | A dairy farmer introduced hybrid Napier grass cultivation on field bunds and available land to ensure fodder availability during dry periods.                  | The practice reduced dependency on external fodder sources and supported better animal health and milk production.        | (Basu <i>et al.</i> , 2026)   |
| Smt. Rina Mondal, Basanti, South 24 Parganas, West Bengal             | A smallholder farmer cultivated hybrid Napier grass near the homestead with organic manure application and regular harvesting.                                 | Continuous supply of nutritious green fodder improved cattle feeding and increased livestock-based income.                | (Mondal <i>et al.</i> , 2022) |

### Conclusion:

Napier grass (*Pennisetum purpureum*) has emerged as a promising climate-resilient forage crop for strengthening fodder security in the coastal saline zone of West Bengal. Its high biomass productivity, perennial growth habit, rapid regeneration, and moderate tolerance to salinity, drought, and short-term waterlogging make it well suited to the challenging coastal environment. Adoption of improved cultivars, scientific crop management, and integrated nutrient and water management practices can further enhance its productivity and forage quality.

Despite these advantages, constraints such as increasing soil salinity, limited availability of quality planting material, and inadequate extension support continue to hinder its large-scale adoption. Future efforts should focus on developing salt-tolerant

cultivars, promoting climate-smart fodder production technologies, and strengthening research-extension and farmer linkages. Integrating Napier grass into sustainable crop-livestock systems will not only ensure year-round green fodder availability but also improve livestock productivity, farm income, and the resilience of coastal farming communities in West Bengal.

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# Nanoparticle-Assisted Enhancement of Fruit Productivity and Quality Under Biotic and Abiotic Stresses

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Fruit crops are indispensable components of human nutrition and global agriculture, providing essential vitamins, minerals, antioxidants, and dietary fiber. However, fruit production is increasingly threatened by various biotic and abiotic stresses, including drought, salinity, temperature extremes, nutrient deficiencies, and pathogen attacks. These stresses significantly reduce fruit yield, quality, and economic returns. Recent advances in nanotechnology have introduced innovative approaches for improving crop resilience and productivity. Nanoparticles (NPs) possess unique physicochemical properties that enable efficient nutrient delivery, enhanced stress tolerance, and improved disease management. Various nanoparticles, including zinc oxide, silicon dioxide, titanium dioxide, silver, and copper oxide nanoparticles, have demonstrated remarkable potential in mitigating environmental stresses and enhancing fruit quality attributes.

## Introductions

Fruit production plays a crucial role in ensuring nutritional security and supporting agricultural economies worldwide. Fruits are rich sources of vitamins, minerals, antioxidants, and phytochemicals that contribute significantly to human health (Slavin & Lloyd, 2012). However, increasing population pressure, climate change, land degradation, and water scarcity pose significant challenges to sustainable fruit production.

Abiotic stresses such as drought, salinity, heat, cold, and nutrient imbalance account for substantial reductions in fruit crop productivity globally. Similarly, biotic stresses caused by fungal, bacterial, viral pathogens, and insect pests lead to severe economic losses (FAO, 2023). Conventional agricultural practices often fail to provide adequate protection against these challenges while maintaining environmental sustainability.

Nanotechnology has emerged as a promising frontier in modern agriculture. Nanoparticles are materials with dimensions ranging between 1 and 100 nanometers and exhibit unique properties such as

increased surface area, enhanced reactivity, and improved delivery efficiency (Fraceto et al., 2016). Their application in horticulture offers new opportunities for improving nutrient utilization, stress tolerance, disease management, and fruit quality. Consequently, nanoparticle-based technologies are gaining increasing attention as sustainable tools for enhancing fruit productivity under challenging environmental conditions.

## Nanoparticles and Their Agricultural Applications

Nanoparticles can be synthesized from metals, metal oxides, polymers, carbon-based materials, and biological sources. In agriculture, commonly used nanoparticles include zinc oxide (ZnO), silicon dioxide (SiO<sub>2</sub>), titanium dioxide (TiO<sub>2</sub>), iron oxide (Fe<sub>2</sub>O<sub>3</sub>), silver (Ag), and copper oxide (CuO) nanoparticles.

Due to their nanoscale size and high surface-to-volume ratio, nanoparticles facilitate efficient nutrient delivery and uptake by plants. Nanofertilizers improve nutrient use efficiency by reducing nutrient losses and ensuring controlled



nutrient release (Zulfiqar et al., 2019). Additionally, nanoparticles can act as carriers for agrochemicals, enabling targeted delivery and reducing environmental contamination.

## **Role of Nanoparticles in Mitigating Abiotic Stresses**

### **Drought Stress**

Drought is one of the most severe environmental constraints affecting fruit production. Water deficit impairs photosynthesis, nutrient uptake, flowering, fruit set, and fruit development. Nanoparticles help plants cope with drought stress through multiple physiological and biochemical mechanisms.

Silicon nanoparticles improve water-use efficiency by enhancing root growth and maintaining cellular water balance. They also stimulate antioxidant defense systems that protect plants from oxidative damage caused by water deficiency (Siddiqui et al., 2015). Zinc oxide nanoparticles have been reported to increase chlorophyll content, photosynthetic activity, and nutrient absorption under drought conditions.

Nanoparticle-mediated enhancement of antioxidant enzymes such as catalase, superoxide dismutase, and peroxidase helps reduce reactive oxygen species (ROS) accumulation, thereby protecting plant tissues from drought-induced injury (Hatami et al., 2016).

### **Salinity Stress**

Salinity affects fruit crops by disrupting osmotic balance and causing ion toxicity. Excess sodium ions interfere with nutrient uptake and metabolic activities, leading to reduced growth and productivity. Nanoparticles alleviate salinity stress by regulating ion transport and enhancing antioxidant defense mechanisms. Silicon and zinc nanoparticles improve potassium retention while reducing sodium accumulation in plant tissues. These effects

contribute to improved physiological performance and stress tolerance (Khan et al., 2017). Furthermore, nanoparticles enhance membrane stability and maintain photosynthetic efficiency under saline conditions, thereby supporting fruit development and yield.

### **Heat and Temperature Stress**

Global warming has increased the frequency of high-temperature events, adversely affecting fruit crops. Heat stress disrupts cellular metabolism and promotes excessive ROS production, resulting in oxidative damage. Titanium dioxide and zinc oxide nanoparticles enhance photosynthetic efficiency and protect cellular structures from thermal injury. Nanoparticles also activate antioxidant defense pathways, reducing oxidative stress and maintaining metabolic functions during high-temperature exposure (Hatami et al., 2016).

### **Nutrient Deficiency Stress**

Micronutrient deficiencies are common in many fruit-growing regions and significantly limit crop productivity. Nanofertilizers provide an effective solution by improving nutrient availability and uptake. Nano-zinc, nano-iron, and nano-boron fertilizers exhibit greater nutrient-use efficiency than conventional fertilizers. Their controlled-release properties ensure prolonged nutrient availability while minimizing nutrient losses through leaching and volatilization (Zulfiqar et al., 2019).

## **Nanoparticles in Managing Biotic Stresses**

### **Disease Management**

Plant diseases caused by fungi, bacteria, and viruses remain major constraints in fruit production systems. Nanoparticles possess antimicrobial properties that can suppress pathogen growth and reduce disease incidence.

Silver nanoparticles are particularly effective against a wide range of plant pathogens due to their



ability to disrupt microbial cell membranes and interfere with metabolic processes (Khan et al., 2019). Copper oxide nanoparticles also exhibit strong antifungal and antibacterial activities. Nanoparticle-based formulations offer advantages such as targeted delivery, controlled release, and reduced pesticide requirements, making them environmentally friendly alternatives to conventional disease management approaches.

### **Pest Control**

Nanotechnology has enabled the development of nanopesticides that improve pest control efficiency while reducing environmental impacts. Nanoparticles can enhance pesticide stability and facilitate controlled release, ensuring prolonged protection against insect pests. These advanced formulations reduce chemical residues and minimize adverse effects on non-target organisms, thereby contributing to sustainable pest management strategies.

### **Influence of Nanoparticles on Fruit Yield and Quality**

Apart from stress mitigation, nanoparticles directly influence fruit productivity and quality attributes. Improved nutrient uptake and physiological performance result in enhanced vegetative growth, flowering, fruit set, and yield. Several studies have reported increased fruit size, weight, firmness, sugar content, vitamin concentration, and antioxidant levels following nanoparticle application. Silicon nanoparticles improve fruit firmness and shelf life by strengthening cell wall structures, while zinc nanoparticles enhance biochemical quality traits and nutrient composition. Nanoparticles also contribute to improved post-harvest performance by reducing physiological disorders and delaying senescence, thereby extending marketability and storage life.

### **Mechanisms Underlying Nanoparticle-Induced Stress Tolerance**

The beneficial effects of nanoparticles are associated with several physiological and molecular mechanisms:

1. Enhanced nutrient uptake and transport.
2. Improved photosynthetic efficiency.
3. Activation of antioxidant defense systems.
4. Regulation of osmotic balance and ion homeostasis.
5. Modulation of stress-responsive gene expression.
6. Improved water-use efficiency.
7. Strengthening of plant defense responses against pathogens.

Collectively, these mechanisms enable plants to withstand adverse environmental conditions while maintaining growth and productivity.

### **Challenges and Future Perspectives**

Despite their promising potential, several challenges remain regarding the widespread adoption of nanoparticle-based technologies in horticulture. Concerns related to environmental safety, nanoparticle accumulation, toxicity, and long-term ecological impacts require comprehensive investigation. Future research should focus on developing biodegradable and environmentally safe nanoparticles, understanding nanoparticle–plant interactions, and evaluating field-level performance under diverse agroecological conditions. Integration of nanotechnology with precision agriculture and digital farming technologies may further enhance resource-use efficiency and sustainability.



## Conclusion

Nanoparticles represent a transformative technology for modern fruit production. Their ability to improve nutrient utilization, enhance tolerance to abiotic stresses, and provide effective protection against diseases and pests offers significant opportunities for sustainable horticultural development. Nanoparticle-based interventions can improve fruit yield, quality, and post-harvest performance while reducing environmental impacts. Although further research is required to address safety concerns and optimize application strategies, nanotechnology holds immense promise for enhancing fruit productivity and resilience under changing climatic conditions.

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# Climate-Smart Horticulture: Strategies for Sustainable Fruit Production in a Changing Climate

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Horticulture is one of the fastest-growing sectors of Indian agriculture and plays a pivotal role in ensuring food and nutritional security, employment generation, and economic development. India is the second-largest producer of fruits and vegetables in the world after China, with fruit cultivation occupying 7.17 million hectares and contributing significantly to agricultural exports and farmers' incomes. Fruit crops such as mango, banana, citrus, apple, guava, grapes, pomegranate, and litchi are not only economically important but also serve as rich sources of vitamins, minerals, antioxidants, and dietary fibre. Their cultivation has become increasingly important in improving livelihoods, diversifying farming systems, and supporting sustainable rural development.

Despite its remarkable growth, the horticulture sector faces unprecedented challenges due to climate change. Rising temperatures, erratic rainfall, prolonged droughts, unseasonal rains, hailstorms, frost events, cyclones, and increasing pest and disease pressures are adversely affecting orchard productivity, fruit quality, and profitability. Unlike annual crops, fruit trees remain in the field for several years, making them particularly vulnerable to long-term climatic variations. Climate-induced stresses not only reduce yields but also impair flowering, pollination, fruit set, fruit development, and postharvest quality, threatening the sustainability of fruit production systems.

To address these challenges, the concept of **Climate-Smart Horticulture (CSH)** has emerged as a sustainable approach that integrates climate adaptation, mitigation, and productivity enhancement. Climate-smart horticulture promotes resource-efficient technologies, resilient production systems, and environmentally friendly management practices that enable farmers to cope with changing climatic conditions while maintaining productivity and conserving natural resources. By combining scientific innovations with traditional knowledge,

climate-smart horticulture offers practical solutions for enhancing resilience, reducing greenhouse gas emissions, improving resource-use efficiency, and ensuring long-term sustainability of fruit production.

This article discusses the concept of climate-smart horticulture, examines the major impacts of climate change on fruit production, and highlights practical strategies and emerging technologies that can help build resilient and sustainable orchard systems.

## Understanding Climate-Smart Horticulture

Climate-smart horticulture is an adaptation of the broader concept of **Climate-Smart Agriculture (CSA)** developed by the Food and Agriculture Organization (FAO). It aims to increase horticultural productivity while enhancing resilience to climate variability and minimizing environmental impacts. Rather than relying solely on increased inputs, climate-smart horticulture emphasizes efficient use of water, nutrients, energy, and other natural resources through innovative technologies and sustainable management practices.

The approach is based on three interconnected pillars:



## 1. Sustainably Increasing Productivity

The primary objective is to maintain or enhance fruit yield and quality without degrading natural resources. Improved varieties, precision nutrient management, efficient irrigation systems, integrated pest management, and scientific canopy management contribute to higher productivity while reducing production costs.

## 2. Building Climate Resilience

Climate-smart practices improve the ability of orchards to withstand climatic stresses such as drought, heat waves, floods, frost, and erratic rainfall. Diversified cropping systems, resilient rootstocks, mulching, rainwater harvesting, and weather-based advisory services help farmers adapt to changing climatic conditions.

## 3. Reducing Environmental Impact

Fruit orchards can contribute to climate change mitigation through carbon sequestration, efficient fertilizer use, renewable energy adoption, and reduced greenhouse gas emissions. Sustainable orchard management also improves biodiversity, soil health, and ecosystem services.

Unlike conventional orchard management, which often depends heavily on chemical inputs and intensive resource use, climate-smart horticulture focuses on improving efficiency, conserving resources, and enhancing ecological sustainability.

### Why Climate-Smart Horticulture Matters

Fruit production is highly sensitive to changes in the environment such as temperature, rainfall, humidity, and seasonal weather patterns. Even slight deviations in climatic conditions during flowering or fruit development can substantially affect yield and quality.

For example:

- Apple cultivation in temperate regions increasingly suffers from inadequate winter chilling, resulting in poor flowering and reduced fruit set.
- Citrus orchards experience greater incidences of fruit drop and sunburn due to rising summer temperatures.
- Mango flowering is disrupted by unseasonal rains and warm winters, reducing fruit production.
- Grapes face increased disease incidence under humid conditions, requiring higher management inputs.
- Banana plantations are frequently damaged by cyclones and strong winds in coastal regions.

These challenges demonstrate the urgent need for production systems that are more resilient and adaptable to climatic uncertainties.

## Climate-Smart Strategies for Sustainable Fruit Production

Adapting fruit production to changing climatic conditions requires a combination of scientific knowledge, improved technologies, and sustainable management practices. Climate-smart horticulture focuses on maximizing productivity while conserving natural resources and enhancing the resilience of orchard ecosystems. The following strategies provide practical approaches for developing sustainable and climate-resilient fruit production systems.

### 1. Selection of Climate-Resilient Varieties and Rootstocks

The choice of planting material is one of the most important decisions in orchard establishment. Climate-resilient cultivars and rootstocks help fruit crops withstand environmental stresses such as



drought, heat, salinity, and emerging pests and diseases while maintaining productivity. Modern breeding programmes have developed cultivars with improved tolerance to abiotic stresses and superior fruit quality. Likewise, the use of appropriate rootstocks enhances water and nutrient uptake, improves tolerance to soil constraints, and increases tree longevity. Farmers should select varieties recommended for their agro-climatic region and adopt certified disease-free planting material from recognized nurseries. Diversifying orchards with early-, mid-, and late-maturing cultivars can also reduce production risks associated with unpredictable weather and extend the harvesting season, providing a more stable income.

## 2. Efficient Water Management

Water scarcity has become one of the greatest constraints to horticultural production. Efficient irrigation management is therefore a cornerstone of climate-smart horticulture using Drip Irrigation, Mulching, Rainwater Harvesting and Smart Irrigation Scheduling using soil moisture sensors, tensiometers, automated irrigation controllers, and weather-based irrigation scheduling helps optimize water use while preventing over-irrigation

## 3. Soil Health Management

Healthy soils are fundamental to resilient orchards. Climate-smart soil management enhances water retention, nutrient availability, and biological activity while reducing land degradation. Important practices include: Regular application of farmyard manure and compost, Vermicomposting, Green manuring, Crop residue recycling, Cover cropping and Reduced soil disturbance. Organic matter improves soil structure, increases microbial diversity, and enhances the soil's capacity to store carbon and water. Improved soil health also strengthens tree resilience during drought and heat stress.

## 4. Integrated Nutrient Management

Balanced nutrition is essential for sustaining fruit production under changing climatic conditions. Excessive dependence on chemical fertilizers not only increases production costs but may also degrade soil quality and increase greenhouse gas emissions. Integrated Nutrient Management (INM) combines organic manures, biofertilizers, and inorganic fertilizers to ensure balanced nutrient supply.

Key components include:

- Soil testing before fertilizer application
- Site-specific nutrient management
- Organic manures and compost
- Biofertilizers such as *Azotobacter*, *Azospirillum*, and phosphate-solubilizing bacteria
- Foliar application of micronutrients where deficiencies occur

Precision nutrient management improves nutrient-use efficiency while minimizing environmental pollution.

## 5. Scientific Canopy Management

Proper canopy architecture enhances light interception, improves air circulation, and facilitates orchard operations.

Scientific pruning and training help:

- Increase photosynthetic efficiency
- Improve fruit colour development
- Reduce disease incidence
- Enhance spray penetration
- Improve harvesting efficiency



Regular removal of diseased, damaged, and overcrowded branches also improves overall tree health and productivity.

## 6. Precision Horticulture

Rapid advances in digital technologies are transforming orchard management. Precision horticulture involves collecting real-time information and applying inputs only where and when required. Major tools include: Global Positioning System (GPS), Geographic Information System (GIS), Remote sensing, Drones, Internet of Things (IoT), Artificial Intelligence (AI).

These technologies assist in:

- Monitoring crop health
- Mapping nutrient deficiencies
- Detecting diseases at an early stage
- Irrigation scheduling
- Yield estimation
- Variable-rate fertilizer application

Precision farming not only improves productivity but also reduces wastage of water, fertilizers, and pesticides.

## 7. Integrated Pest and Disease Management (IPM)

Climate change has altered pest dynamics, making integrated management increasingly important. An effective IPM programme includes:

- Regular orchard monitoring
- Pest forecasting
- Resistant cultivars
- Biological control agents
- Botanical pesticides

- Pheromone traps
- Sticky traps
- Judicious pesticide use only when economic thresholds are exceeded

Maintaining orchard sanitation by removing infected plant debris also reduces inoculum build-up and disease spread.

## 8. Pollinator Conservation

Many fruit crops depend on insect pollinators for successful fruit set and yield. However, pollinator populations are declining due to habitat loss, pesticide misuse, and climate change.

Farmers can promote pollinator activity by:

- Conserving flowering plants around orchards
- Reducing pesticide application during flowering
- Using bee-friendly pesticides
- Installing honeybee colonies where appropriate
- Maintaining biodiversity within orchard ecosystems

Healthy pollinator populations improve fruit set, yield, and fruit quality.

## 9. Diversification and Mixed Farming Systems

Diversified farming systems are generally more resilient to climatic shocks than monoculture orchards. Farmers can enhance resilience by intercropping i.e. growing legumes or medicinal plants between fruit trees improves soil fertility, reduces weed growth, and generates additional income. Agroforestry systems also increase biodiversity and contribute to carbon sequestration.



## 10. Carbon-Smart Orchard Management

Fruit orchards have considerable potential to capture atmospheric carbon and reduce greenhouse gas emissions. Climate-smart orchard practices include:

- Conservation tillage
- Cover cropping
- Organic amendments
- Reduced burning of crop residues
- Efficient fertilizer use
- Solar-powered irrigation systems

These practices contribute to climate change mitigation while improving long-term soil fertility.

### Benefits of Climate-Smart Horticulture

Adoption of climate-smart technologies provides multiple benefits:

- Improved fruit yield and quality
- Better water-use efficiency
- Enhanced nutrient-use efficiency
- Reduced production costs over time
- Greater resilience to drought and heat stress
- Improved soil health
- Lower greenhouse gas emissions
- Increased farm profitability
- Sustainable use of natural resources
- Improved long-term orchard productivity

## Government Initiatives Supporting Climate-Smart Horticulture in India

The Government of India has launched several programmes to strengthen sustainable horticulture and improve farmers' resilience to climate change.

1. Mission for Integrated Development of Horticulture (MIDH)
2. Pradhan Mantri Krishi Sinchayee Yojana (PMKSY)
3. National Mission for Sustainable Agriculture (NMSA)
4. Digital Agriculture Mission
5. PM-KUSUM Scheme

### Future Perspectives

Future priorities include:

- Development of climate-resilient cultivars and rootstocks
- Application of genomic-assisted breeding
- Wider adoption of AI and digital agriculture
- Expansion of protected cultivation
- Improved climate forecasting and advisory services
- Sustainable water management
- Carbon-neutral orchard production systems
- Greater use of renewable energy
- Strengthening farmer training and capacity building

Building resilient orchard ecosystems will be essential for maintaining productivity while conserving natural resources and biodiversity.





## Conclusion

Climate change poses significant challenges to sustainable fruit production by affecting flowering, fruit development, productivity, and quality. Rising temperatures, erratic rainfall, extreme weather events, and increasing pest and disease pressures demand a shift from conventional orchard management towards more resilient production systems. Climate-smart horticulture along with emerging technologies offers a practical and sustainable pathway to address these challenges by integrating improved planting materials, efficient

water and nutrient management, healthy soils, precision technologies, integrated pest management, and environmentally responsible production practices. These approaches not only enhance resilience to climate variability but also improve productivity, resource-use efficiency, and farm profitability while conserving natural resources.

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## Fly Ash: Turning Industrial Waste into a Valuable Resource for Sustainable Agriculture

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Fly ash, a by-product of coal-based thermal power plants, presents significant environmental challenges due to its large-scale generation and disposal requirements. However, when managed effectively, it can serve as a valuable resource for sustainable agriculture. Rich in essential macro- and micronutrients, fly ash improves soil fertility, enhances crop productivity, and acts as an effective soil conditioner. It can also be used as a source of plant nutrients, a component in pest management, and for reclaiming degraded soils. Owing to its alkaline nature, fly ash can help amend acidic soils and reduce the need for lime, contributing to lower carbon emissions. The judicious use of fly ash not only promotes sustainable waste management but also supports environmentally friendly and resource-efficient farming practices.

### 1. Introduction

Fly ash is a fine, mineral-rich powder generated during coal combustion in thermal power plants. It is collected from flue gases using electrostatic or cyclonic precipitators before being released into the atmosphere. Its composition varies depending on the type of coal, combustion conditions, and ash collection methods. Although fly ash is an industrial by-product, it is recognized by the Organisation for Economic Co-operation and Development (OECD) as a reusable material rather than a waste. Many countries have successfully utilized fly ash in construction and infrastructure development, while its agricultural applications are gaining increasing attention. Owing to its rich mineral content, fly ash can improve soil properties, enhance crop productivity, and reclaim degraded soils when used judiciously. Research conducted worldwide has demonstrated its potential as a sustainable soil amendment, offering an environmentally friendly solution for reducing the economic and ecological

challenges associated with fly ash disposal (Basu *et al.*, 2009).

### 2. Major Classes of Fly Ash

Fly ash is primarily classified according to the type of coal used for combustion, as coal composition strongly influences its physical and chemical properties. Coal ranks, in increasing order of carbon content, include **peat, lignite, sub-bituminous, bituminous, and anthracite**. In India, fly ash is mainly produced from **sub-bituminous, bituminous, and lignite** coals, which generally contain **35–50% ash**.

Based on its chemical composition, particularly the combined content of **silica (SiO<sub>2</sub>), alumina (Al<sub>2</sub>O<sub>3</sub>), and iron oxide (Fe<sub>2</sub>O<sub>3</sub>)**, fly ash is classified into **Class F** and **Class C**. **Class F fly ash**, produced mainly from anthracite and bituminous coals, contains low calcium oxide (CaO) content (typically **less than 7%**) and exhibits pozzolanic properties. In contrast, **Class C fly ash**, derived from lignite and sub-bituminous coals, contains higher levels of



calcium oxide (up to **30%**) and possesses both cementitious and liming properties, making it particularly useful for soil amendment and acidic soil reclamation (Wang and Wu, 2006; Upadhyay and Kamal, 2007).

### 3. Physicochemical Properties of Fly Ash

The physicochemical properties of fly ash are influenced by the type of coal, combustion conditions, particle size, ash collection system, and storage practices (Basu et al., 2009). Generally, fly ash is a **fine, silt-sized material** with particles mostly smaller than **0.01 mm**, making it comparable to silty loam soil (Chang et al., 1977). Its colour varies from dark grey to light grey, reflecting differences in carbon and calcium oxide contents. The specific gravity typically ranges from **1.6 to 3.1**, while its **low bulk density, high porosity, and excellent water-holding capacity** make it suitable for improving soil physical properties (McLaren and Digioia, 1987; Mishra, 2008; Mishra and Das, 2010).

Chemically, fly ash is predominantly composed of **silica ( $\text{SiO}_2$ ), alumina ( $\text{Al}_2\text{O}_3$ ), and iron oxide ( $\text{Fe}_2\text{O}_3$ )**, along with calcium, magnesium, potassium, phosphorus, and trace amounts of micronutrients such as manganese, copper, chromium, and nickel (Salunkhe and Mandal, 2014; Mishra and Das, 2010). Mineralogical studies show that **quartz and mullite** are the major crystalline minerals, while the remaining fraction consists largely of amorphous ferro-aluminosilicate material (Upadhyay and Kamal, 2007).

The **pH of fly ash ranges from 4.5 to 12.0**, depending on its sulphur and calcium contents. Fly

ash derived from anthracite coal is generally acidic, whereas that produced from lignite is alkaline due to its higher calcium content. Indian fly ash is typically **low in sulphur but rich in ash**, making it suitable for agricultural use as a **soil amendment and supplementary nutrient source**, particularly for improving soil fertility and productivity when applied at recommended rates (Basu et al., 2009; Singh et al., 2010; Shaheen et al., 2014).

### 4. Influence of Fly Ash on Soil Biological Properties

Fly ash can influence soil biological properties by altering microbial activity, enzyme function, and nutrient cycling. When applied at recommended levels, it enhances the activity of key soil enzymes such as **dehydrogenase, urease, and phosphatases**, which are involved in organic matter decomposition, nutrient mineralization, and maintenance of soil fertility. Moderate fly ash application also increases soil microbial biomass by supplying essential nutrients that stimulate microbial metabolism (Pati and Sahu, 2004; Yeledhalli et al., 2007).

Research indicates that combining fly ash with **farmyard manure (FYM)** or other organic amendments further improves soil biological health by increasing populations of beneficial microorganisms such as **Rhizobium, Azotobacter, Azospirillum**, phosphate-solubilizing bacteria, and **Bacillus** species. These microorganisms enhance nitrogen fixation, phosphorus solubilization, and nutrient availability, thereby supporting plant growth and improving soil fertility (Bhattacharya and Chattopadhyaya, 2004).



However, excessive application of fresh or unweathered fly ash may suppress microbial respiration, reduce enzyme activity, and disrupt nitrogen transformation processes due to its high soluble salt content and trace elements. Weathering and proper application rates help minimize these adverse effects, making fly ash a valuable amendment for improving soil biological quality and promoting sustainable crop production when used judiciously (Basu *et al.*, 2009; Murgan and Vijayarangam, 2013).

### 5. Fly Ash as a Soil Amendment for Acidic Soils

Indian fly ash is generally **alkaline in nature**, making it a promising alternative to agricultural lime for the reclamation of acidic soils. Owing to its high calcium (Ca) and magnesium (Mg) content, fly ash not only neutralizes soil acidity but also supplies essential plant nutrients that support crop growth. Studies have shown that fly ash application increases soil pH, improves nutrient availability, and enhances crop biomass and grain yield. Its ability to improve soil physical and chemical properties makes it particularly beneficial for restoring degraded soils and wastelands. When applied at recommended rates, fly ash serves as an effective soil conditioner, contributing to improved soil fertility, higher crop productivity, and sustainable agricultural practices (Ukwattage *et al.*, 2013).

### 6. Fly Ash for Enhancing Crop Productivity

Fly ash has considerable potential to improve agricultural productivity when applied at appropriate rates. Rich in essential nutrients and beneficial

minerals, it enhances seed germination, plant growth, nutrient uptake, and crop yield by improving soil structure, water-holding capacity, and nutrient availability. Several studies have reported significant increases in the growth and yield of crops such as wheat, maize, rice, sunflower, sesame, mustard, pigeon pea, mung bean, urd bean, and chilli following fly ash application in combination with recommended fertilizer doses or organic manures. In addition to supplying macro- and micronutrients, fly ash can also serve as a soil conditioner and has potential applications as an insecticide carrier and in integrated nutrient management systems (Das *et al.*, 2013; Rout *et al.*, 2016).

However, the benefits of fly ash depend on its application rate. Moderate doses generally promote crop growth and improve soil fertility, whereas excessive application may increase the accumulation of certain trace elements and negatively affect plant growth and yield. Therefore, fly ash should be applied judiciously based on soil characteristics, crop requirements, and recommended agronomic practices. Its proper utilization offers an environmentally sustainable approach to recycling industrial by-products while improving soil health, crop productivity, and resource-use efficiency (Singh *et al.*, 2008; Thakare *et al.*, 2013; Ukwattage *et al.*, 2013).

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# From Bt Cotton to CRISPR Rice: India's Evolving Agricultural Biotechnology Landscape

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Agricultural biotechnology has transformed crop improvement by providing innovative tools to enhance productivity, pest resistance, and climate resilience. In India, this journey began with the commercialization of Bt cotton and has now advanced towards precise genome editing using CRISPR-Cas9 technology. While genetically modified crops have demonstrated significant agricultural benefits, they have also raised concerns regarding biosafety, environmental impact, and public acceptance. In contrast, gene editing enables targeted modifications in plant genomes, often without introducing foreign DNA, offering new opportunities for sustainable crop improvement. With growing indigenous research and evolving regulatory policies, India is gradually embracing next generation breeding technologies. Understanding the differences between GM crops and gene-edited crops is essential for informed decision-making and the future development of resilient and sustainable agriculture.

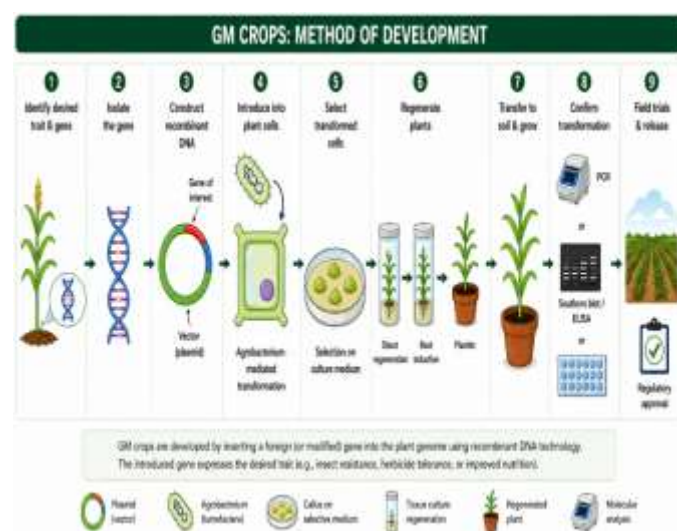
## Introduction

India's agricultural journey has been one of resilience and reinvention. From the Green revolution of the 1960s to today's climate-stressed farmlands, the country has continuously sought scientific solutions to ensure food security for its 1.4 billion people. In a nation where agriculture defines livelihoods and security, biotechnology has reshaped farming horizons of the country. From the early days of genetically modified crops to the cutting-edge era of gene-edited staples like rice, India's journey reflects scientific ambition, regulatory caution, and societal debate.

## Understanding GM Crops

Genetically Modified crops are plants whose DNA is altered using genetic engineering technology to introduce desirable traits such as pest resistance, drought tolerance, and nutritional enhancement etc. GM crops were first commercialized in the USA in

1994 with the Flavr Savr tomato, engineered to delay ripening.



## Bt Cotton: India's First Big Leap

Bt cotton is the only genetically modified crop approved for commercial cultivation in India (since 2002), developed using a gene from bacterium *Bacillus thuringiensis* that provides resistance



against bollworms. It now covers over 90 % of cotton area in India which is around 12 million hectares.

| Key Impacts                                                                               | Setbacks and Challenges                                                                     |
|-------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------|
| Increased cotton production by ~193% between 2002 and 2014                                | Post-2015, yields have declined due to pest resistance and outdated biotechnological traits |
| Helped India's become the 2 <sup>nd</sup> largest cotton exporter globally by early 2010s | Regulatory delays have limited introduction of newer Bt traits                              |

### GM crops beyond Cotton: Pending GM crops Approvals

**Bt Brinjal:** Approved by Genetic Engineering Appraisal Committee (GEAC) in 2009, but was put on a moratorium.

**HT-Bt Cotton:** Herbicide tolerant GM variant, is not approved for commercial use in India.

**GM Mustard (DMH-11):** Granted environmental clearance in 2022, but its commercial release is pending in the Supreme Court.

### Key Benefits and Concerns of GM Crops

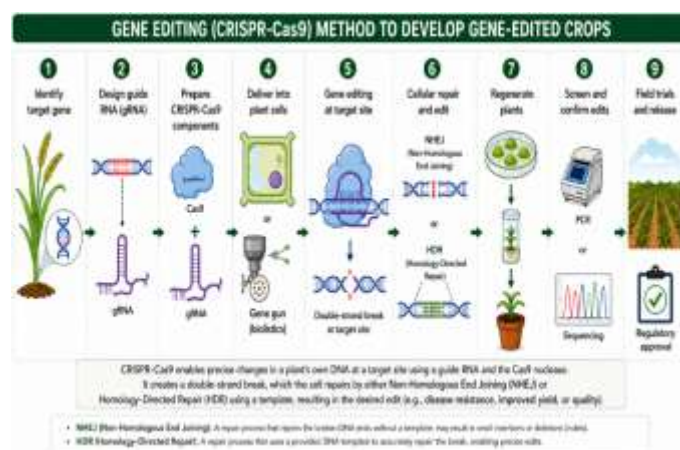
Amid ongoing trade negotiations, the US is pushing India to open its agriculture market to GM crops. However, India has firmly stated that agriculture and dairy are 'sacrosanct red lines', warning that allowing GM crop imports could threaten farmers' livelihoods and safety.

| Benefits                                              | Concerns                                          |
|-------------------------------------------------------|---------------------------------------------------|
| Higher productivity                                   | Resistance development                            |
| Enhanced pest and disease resistance<br>Eg. Bt cotton | Biodiversity impact: large scale monocropping may |

|                                                            |                                                                                             |
|------------------------------------------------------------|---------------------------------------------------------------------------------------------|
|                                                            | affect ecological balance and native varieties                                              |
| Climate resilience and resource efficiency Eg. C4 rice     | Gene flow to the wild species leading to herbicide resistant super weeds                    |
| Nutritional enhancement (Biofortification) Eg. Golden rice | Dependency of farmers on the private companies for patented seeds each season               |
| Biopharming and Phytoremediation using GM crops            | Consumer concerns and activism influence adoption and policy decisions                      |
| Improved farmer returns                                    | Regulatory complexity as biosafety approvals require rigorous and time consuming evaluation |

### Gene Editing through CRISPR-Cas9: A New Frontier

Gene editing is a biotechnology technique which enables precise modification of crop genomes, without introducing foreign DNA. The real breakthrough in gene editing came in 2012 with CRISPR-Cas9, a simple, fast, highly precise and affordable system. It uses a guide RNA to locate target gene and the Cas9 enzyme cuts DNA at the specific site.



### Key Developments in Agriculture in India using CRISPR-Cas9 system

ICAR (Indian Council of Agricultural Research) has developed India's first genome-edited (GE) rice varieties, also India became first country in the world to develop GE rice varieties. These new varieties were developed using CRISPR-Cas9 system.

| Achievement        | Developed by                                                  | Traits developed                                                                         |
|--------------------|---------------------------------------------------------------|------------------------------------------------------------------------------------------|
| DRR Dhan 100 Kamla | ICAR-IIRR (Indian Institute of Rice Research), Hyderabad      | Improvement of variety, 'Samba Mahsuri' by targeting the CKX2 (Cytokinin Oxidase 2) gene |
| Pusa DST Rice 1    | ICAR-IARI (Indian Agricultural Research Institute), New Delhi | Improved version of the fine grain rice MTU1010 (Cottondora Sannalu)                     |

### Indigenous CRISPR Tools in India

India is not only using CRISPR technology but has also developed home-grown (indigenous) CRISPR-systems to reduce dependence on foreign patents and improve precision.

| Tool Name                                  | Developed by                                              | Type                               | Significance                     |
|--------------------------------------------|-----------------------------------------------------------|------------------------------------|----------------------------------|
| FnCas9 ( <i>Francisella novicida</i> Cas9) | CSIR (Council of Scientific and Industrial Research)-IGIB | Cas9 variant (Gene-editing enzyme) | Indigenous alternative to SpCas9 |

|                                                       |                                                 |                                                          |                                                           |
|-------------------------------------------------------|-------------------------------------------------|----------------------------------------------------------|-----------------------------------------------------------|
|                                                       | (Institute of Genomics and Integrative Biology) |                                                          |                                                           |
| enFnCas9 (Enhanced FnCas9)                            | CSIR-IGIB                                       | Improved Cas9 variant                                    | Next-generation Indian CRISPR tool                        |
| FELUDA (FnCas9 Editor Linked Uniform Detection Assay) | CSIR-IGIB                                       | CRISPR-based diagnostic platform                         | First indigenous CRISPR diagnostic kit developed in India |
| GlowCas9                                              | Bose Institute, Kolkata                         | CRISPR protein (lights up while performing gene editing) | To cut and correct DNA with accuracy                      |

### Difference between GM Crops and Gene-edited crops

| FEATURE                                                                                                      | GM CROPS                                                                         | GENE-EDITED CROPS                                                                                                          |
|--------------------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------|
|  <b>DEFINITION</b>        | Crops developed by inserting a foreign (or modified) gene into the plant genome. | Crops developed by making precise changes in the plant's own DNA at a specific target site.                                |
|  <b>GENETIC CHANGE</b>    | Addition of new gene(s) from another species.                                    | Precise edit (addition, deletion or replacement) in the existing gene.                                                     |
|  <b>FOREIGN DNA</b>       | Yes, foreign DNA is inserted and present in the final product.                   | No, no foreign DNA remains in the final product.                                                                           |
|  <b>TECHNOLOGY USED</b>   | Recombinant DNA technology using vectors (e.g., plasmids) and Agrobacterium.     | Genome editing tools: CRISPR-Cas9, ZFNs (Zinc Finger Nucleases), TALENs (Transcription Activator-Like Effector Nucleases). |
|  <b>OBJECTIVE</b>         | Introduce new traits by adding foreign genes.                                    | Improve existing traits by making precise changes in native genes.                                                         |
|  <b>PRECISION</b>         | Low – random integration; may affect other genes.                                | High – targeted edit at specific DNA sequence.                                                                             |
|  <b>COST</b>              | High – complex transformation and screening.                                     | Lower – targeted editing with faster development.                                                                          |
|  <b>PUBLIC PERCEPTION</b> | Lower acceptance in many countries due to foreign DNA.                           | Higher acceptance as no foreign DNA remains.                                                                               |



### Regulatory Framework in India: GM crops vs Gene-edited crops

India regulates both under Environment (Protection) Act, 1986 and 1989 Rules for Manufacture, Use, Import, Export & Storage of Hazardous

Microorganisms/Gnetically engineered organisms. However, the treatment differs, especially after the 2022 policy exemption by MoEFCC (Ministry of Environment, Forest and Climate Change) for certain gene-edited plants.

| GM (Transgenic) Crops                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                   | Gene-Edited Crops (CRISPR-based)                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                    |
|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <p><b>Regulatory landscape</b></p> <p><b>1. Advisory Committees</b></p> <ul style="list-style-type: none"> <li>The Recombinant DNA Advisory Committee (RDAC)</li> </ul> <p><b>2. Approval Committees</b></p> <ul style="list-style-type: none"> <li>Institutional Biosafety Committee (IBSC)</li> <li>Review Committee on Genetic Manipulation (RCGM)</li> <li>Genetic Engineering Appraisal Committee (GEAC)</li> </ul> <p><b>3. Monitoring Committees</b></p> <ul style="list-style-type: none"> <li>State Biotechnology Coordination Committee (SBCC)</li> <li>District Level Committee (DLC)</li> </ul> <p><b>Key Regulatory Features</b></p> <ul style="list-style-type: none"> <li>Full biosafety and environmental risk assessment (lab, greenhouse and multilocation trials)</li> <li>Mandatory review and approval by the GEAC under MoEFCC</li> <li>Public consultation in some cases</li> <li>Post-release monitoring required</li> <li>Longer approval timelines</li> </ul> | <p><b>Regulatory Category (India, 2022 reform)</b></p> <ul style="list-style-type: none"> <li><b>SDN-1 (Site Directed Nucleases):</b> Small insertions/deletions via repair (no foreign DNA involved)</li> <li><b>SDN-2:</b> Small targeted changes using a repair template (no foreign DNA)</li> <li><b>SDN-3:</b> Larger insertions, may involve foreign DNA (treated like GM)</li> </ul> <p><b>Key Regulatory Features</b></p> <ul style="list-style-type: none"> <li>SDN-1 and SDN-2 are exempt from stringent GEAC approval (2022 MoEFCC notification)</li> <li>Cleared at the institutional biosafety level</li> <li>Faster field testing and release pathway</li> <li>No requirement for full transgenic-style biosafety dossier if no foreign DNA remains</li> <li>SDN-3 continues to be regulated like GM crops</li> </ul> |



## Why are Gene-edited crops regulated differently from GM crops?

India regulates GM crops more strictly because they contain foreign DNA, which raises ecological and food safety concerns requiring extensive biosafety assessment. In contrast, gene-edited crops under SDN-1 and SDN-2 categories do not involve foreign gene insertion and often mimic natural mutations, resulting in a lower perceived risk profile. Therefore, India adopted a differentiated, risk-based regulatory approach in 2022 to promote innovation while maintaining biosafety safeguards.

### Conclusion

The debate between GM crops and gene editing is not merely scientific, it is regulatory, ethical, and

societal. While GM technology marked the first revolution in genetic crop improvement, gene editing presents its refined and more precise successor. India's recent regulatory frameworks and the development of genome-edited rice signal a strategic shift toward innovation driven, yet biosafety conscious agriculture. Moving forward, the challenge lies not in choosing one technology over the other, but in adopting science based regulation, transparent communication, and farmer-centric implementation to achieve climate-resilient agriculture, nutritional security, and sustainable productivity for a rapidly growing nation.

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## The Hidden Environmental Cost of Organic Fertility Sources: Greenhouse Gas Emissions and Climate Change Implications

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The increasing adoption of organic farming has been driven by its ability to improve soil health, recycle agricultural wastes, and reduce dependency on synthetic fertilizers. This article examines the contribution of commonly used organic amendments, including farmyard manure, compost, poultry manure, slurry, digestate, and green manure, to greenhouse gas (GHG) emissions during storage, processing, and field application. Evidence from recent global studies indicates that these materials can release greenhouse gases like carbon dioxide (CO<sub>2</sub>), methane (CH<sub>4</sub>), and nitrous oxide (N<sub>2</sub>O) through microbial decomposition, nitrification, and denitrification processes. The article also discusses how rising GHG concentrations influence temperature, rainfall patterns, and the timing of crop growth stages, thereby affecting agricultural productivity and crop calendars. Importantly, the review emphasizes that the presence of GHG emissions from organic amendments should not be interpreted as evidence that organic farming is environmentally inferior to conventional agriculture.

### Introduction

Larger agricultural land area and their exhaustive management practices, have a substantial impact on the earth's carbon and nitrogen cycles and due to various agricultural activities, greenhouse gases especially carbon dioxide (CO<sub>2</sub>), methane (CH<sub>4</sub>) and nitrous oxide (N<sub>2</sub>O) are being exposed into the atmosphere. Although, the application of animal manure to the agricultural soil not only improves soil health and agricultural production but also has a significant impact on GHGs emissions (Shakoor *et al.*, 2021). The dairy industries face a major challenge in managing manure, a byproduct of dairy operations. A large quantity of manure accumulated in dairy facilities a lot of issues, including bad odour and greenhouse gas (GHG) emissions. One way to overcome this challenge is the application of dairy manure to croplands, which not only helps to manage excess amounts of manure but also provides agronomic benefits to crops. There are three major GHGs relevant to agro based systems: carbon dioxide

(CO<sub>2</sub>), nitrous oxide (N<sub>2</sub>O), and methane (CH<sub>4</sub>). The main agricultural source of soil CO<sub>2</sub> emissions is respiration by soil micro-organisms, including micro-flora and fauna. Dairy manure is known to introduce substantial amounts of microbial biomass C into the soil, accelerating microbial respiration and leading to higher soil CO<sub>2</sub> emissions. Recently, significant attention has been given to N<sub>2</sub>O emissions due to its global warming potential (GWP) that is 273 times greater than CO<sub>2</sub>. Agriculture soil contributes 68 % of global N<sub>2</sub>O emissions, and the main processes responsible for N<sub>2</sub>O production are nitrification and denitrification (Brar *et al.*, 2025). Modern industrial agriculture has been recognized as a significant source of agricultural GHG emission; to mitigate the problem the adoption of regenerative organic agriculture has been proposed as a solution with the potential to reduce GHG emissions from agricultural production. However, there is a lack visible on-the-ground studies reporting on the



climate impacts of organic agriculture (Graham *et al.*, 2025).

### ➤ Escaping from the synthetic fertilizers but inviting the greenhouse gasses instead:

Organic farming has gained widespread attention as a sustainable alternative to conventional agriculture because it reduces reliance on synthetic fertilizers and supports long-term soil and environmental health. Organic nutrient sources such as farmyard manure, compost, poultry manure, slurry, digestate, and green manure are widely used to improve soil fertility and recycle agricultural wastes. However, these materials can also release greenhouse gases (GHGs), including carbon dioxide (CO<sub>2</sub>), methane (CH<sub>4</sub>), and nitrous oxide (N<sub>2</sub>O), during storage, decomposition, and after their application to agricultural soils. These emissions are primarily driven by microbial processes that break down organic matter under varying soil and environmental conditions.

- CO<sub>2</sub> is released through microbial respiration due to the decomposition of organic matter.

Organic matter + O<sub>2</sub> → CO<sub>2</sub> + H<sub>2</sub>O + Energy

- Methane (CH<sub>4</sub>) is mainly produced under oxygen deficient (anaerobic) conditions, such as:

Fresh manure heaps, slurry lagoons, waterlogged soils, flooded rice fields. Methanogenic microorganisms convert organic carbon into methane.

- N<sub>2</sub>O is the most important greenhouse gas associated with agricultural fertilization, produced during nitrification and denitrification. These microbial processes occur when nitrogen from manure or compost becomes available in soil.

Despite these emissions, it would be inaccurate to conclude that organic farming is inherently more

harmful to the climate than conventional farming. Organic production systems often provide important environmental benefits, including greater soil organic carbon storage, enhanced soil biodiversity, improved nutrient cycling, and reduced dependence on the energy-intensive manufacture of synthetic fertilizers. As a result, the overall climate impact of organic farming depends not only on the quantity of greenhouse gases emitted from organic amendments but also on the balance between emissions, carbon sequestration, and management practices (Walling *et al.*, 2020).

### ➤ Some worldwide reports as a form of evidence:

- A comprehensive review of 388 measurements reported the following average emissions from manure composting:

| Greenhouse gas                   | Mean emission                               | Equivalent per tonne of composted manure  |
|----------------------------------|---------------------------------------------|-------------------------------------------|
| Methane (CH <sub>4</sub> )       | 2.82 g kg <sup>-1</sup> feedstock           | 2.82 kg CH <sub>4</sub> t <sup>-1</sup>   |
| Nitrous oxide (N <sub>2</sub> O) | 0.354 g kg <sup>-1</sup> feedstock          | 0.354 kg N <sub>2</sub> O t <sup>-1</sup> |
| CO <sub>2</sub> -equivalent      | ≈184 kg CO <sub>2</sub> -eq t <sup>-1</sup> | Total climate impact                      |

These values are averages from many composting experiments and vary considerably depending on compost management (Nordahl *et al.*, 2023).

- The UNFCCC Clean Development Mechanism recommends the following default emission factors for 1 tonne of organic waste composted:

| Gas | Emission factor |
|-----|-----------------|
|-----|-----------------|



|                  |                            |
|------------------|----------------------------|
| CH <sub>4</sub>  | 2.0 kg tonne <sup>-1</sup> |
| N <sub>2</sub> O | 0.2 kg tonne <sup>-1</sup> |

These are conservative default values used in greenhouse gas accounting.

- **A global meta-analysis of 422 observations from 12 countries estimated the following N<sub>2</sub>O emission factors:**

| Organic amendment                 | N <sub>2</sub> O emission factor (% of N applied emitted as N <sub>2</sub> O-N) |
|-----------------------------------|---------------------------------------------------------------------------------|
| Animal slurry                     | 1.21%                                                                           |
| Solid farmyard manure             | 0.35%                                                                           |
| Compost                           | 0.02%                                                                           |
| Average of all organic amendments | 0.57%                                                                           |

This indicates that animal slurry and fresh manures emit substantially more N<sub>2</sub>O than mature compost (Charles *et al.*, 2017).

- **Changes in climate and crop calendar as a result of rising temperature due to greenhouse gases:**

The excessive emission of greenhouse gases (GHGs), particularly carbon dioxide (CO<sub>2</sub>), methane (CH<sub>4</sub>), and nitrous oxide (N<sub>2</sub>O), has accelerated global climate change, resulting in rising temperatures, altered precipitation patterns, and an increased frequency of extreme weather phenomena (IPCC, 2023).

These climatic changes have been significantly disrupted agricultural systems by affecting crop

calendars, including the time of sowing, flowering, maturity, and harvesting (Rosenzweig *et al.*, 2014).

Moreover, elevated temperatures increase evapotranspiration and water demand, while erratic weather conditions complicate farm management and increase the possibility of pest and disease outbreaks. In South Asia, including India, climate-induced shifts in crop calendars have become increasingly evident, particularly for cereal, oilseed, and pulse crops, posing serious challenges towards food security and sustainable agricultural production (IPCC, 2023; FAO, 2022).

### ➤ **Management Across the Organic Input Lifecycle: Field Application:**

Organic manure application has a lower profile soil carbon inputs with reduced yield and weed tillage. Developing management frameworks across different agroclimatic zone is required to enhance soil inorganic and organic carbon stocks. The following scientific strategies focus on maintaining soil physical health and water dynamics without disturbing crop yield performance while reducing overall greenhouse gas footprint.

| Management practice                        | Predictive results                                                                                                                | Citation                        |
|--------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------|---------------------------------|
| Conservation Tillage                       | It reduced CO <sub>2</sub> production by limiting microbial oxidation of soil organic carbon, and increase topsoil carbon stocks. | Lorenz & Lal (2016),            |
| High-Residue Cover Cropping & Green Manure | This practice can sequence up to 1.65 Mg CO <sub>2</sub> per hector per year and reduced N <sub>2</sub> O flush.                  | Biernat <i>et al.</i> , (2020), |
| Alternate                                  | This management                                                                                                                   | Lorenz                          |



|                                                                         |                                                                                                                                                                   |                               |
|-------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------------------------------|
| Wetting & Drying (AWD) in Rice                                          | practice disrupts anaerobic pathways that suppresses methane generation by 30% to 50% but it requires proper irrigation schedule to avoid N <sub>2</sub> O flush. | & Lal (2016),                 |
| Pyrolytic Biochar Co-Application with Organic Manure                    | This management practices reduce N <sub>2</sub> O up to 36%, but high application rate can alter soil pH and EC.                                                  | Liang <i>et al.</i> , (2024)  |
| Mineral optimization                                                    | This practice promote mineral associated organic matter binding that enhanced long term SOC persistence, but this practice can alter soil alkalinity.             | Chen, <i>et al.</i> , (2022)  |
| Controlled aerobic composting with plant-based nitrification inhibitors | Biological nitrification inhibitor reduced Nitrosomonas bacterial pathways that reduced N <sub>2</sub> O released up to 35%,                                      | Ahmed, <i>et al.</i> , (2023) |

### ➤ Conclusion:

Organic fertility sources contribute to greenhouse gas emissions through microbial decomposition, particularly releasing CO<sub>2</sub>, CH<sub>4</sub>, and N<sub>2</sub>O during storage and field application. However, these emissions do not outweigh the broader environmental benefits of organic farming when managed effectively. Adopting improved manure management, controlled composting, biochar integration, and conservation practices can minimize emissions while maintaining soil fertility, enhancing

carbon sequestration, and supporting climate-resilient and sustainable agricultural production.

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# Nanofortification: A Nanotechnology-Driven Approach to Sustainable Crop Nutrition

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Diets that supply enough calories can still leave people short of the vitamins, minerals, and trace elements the body needs, a gap widely known as hidden hunger. Conventional food fortification, alongside agronomic and genetic biofortification, has narrowed this gap over the past century, but each of these routes carries real drawbacks: nutrients lost during processing, poor absorption once ingested, and, for breeding-based approaches, long development timelines that struggle to keep pace with local needs. Nanofortification, which uses engineered nanoparticles and nanoscale carriers to place micronutrients directly and efficiently within crops, has emerged as a more targeted response to these limitations. This article follows the shift from classical fortification methods to nanoscale nutrient delivery, compares the two approaches directly, describes the main techniques now used to apply nanoparticles in the field, and reviews two independent studies one in wheat, one in rice that illustrate both the gains nanofortification can deliver and the risks that appear once dosing moves beyond an optimal range. Taken together, the evidence suggests that carefully dosed nanofortification can measurably improve germination, biomass, pigment synthesis, and grain nutrient content, while poorly judged concentrations can just as easily become harmful. Continued research into safe dosing and supportive regulation will determine how much of this promise reaches ordinary farms.

## Introduction

Across many parts of the world, an unusual paradox persists that people consume enough food to meet their daily energy needs, yet their diets still fail to supply enough of the micronutrients required for normal growth, immunity, and cognitive development. This gap is known as hidden hunger, and closing it has driven nearly a century of effort to fortify foods and crops with vitamins, minerals, and trace elements. In broad terms, fortification means deliberately adding nutrients back into a food system to correct or prevent such deficiencies at a population scale. Yet the tools used to pursue this goal carry practical drawbacks like nutrients breaking down during storage and cooking, the human gut absorbs only a fraction of what is added, and altering a food's mineral or vitamin content can change how it tastes or feels. These shortcomings have pushed researchers toward a newer, more precise strategy called nanofortification, in which engineered nanomaterials

or nanoscale carriers ferry nutrients into crops with far greater control than conventional methods allow, while also strengthening plants against environmental stress.

## From Classical Fortification to the Nanoscale: Five Stages of Evolution

Nutrient enrichment in agriculture and food systems has developed through five broad, overlapping stages, each building on the limitations of the one before it.

**1. Mass/Conventional Fortification (1920s–1940s):** National governments began fortifying diets at scale, enriching table salt with iodine and wheat flour with iron to curb widespread deficiency diseases. Aimed at human nutrition rather than crop science, this laid the conceptual groundwork on which every later strategy would build (Dwyer et al., 2015).



### 2. Agronomic Biofortification (1960s–1980s):

Attention turned to the field itself, as zinc, iron, and manganese-enriched fertilisers were applied to soil to raise nutrient levels in crops. The approach struggled with efficiency: much of what was applied never reached the plant, instead seeping into surrounding soil and water systems (Leonardi et al., 2021).

### 3. Genetic Biofortification (1990s–2000s):

Breeding initiatives such as HarvestPlus developed staple varieties of rice, wheat, maize, and beans carrying naturally higher micronutrient levels from the seed onward. The method is durable once established but inherently slow, since new varieties can take a decade or more to release and rarely perform equally well across every climate zone (Bouis and Saltzman, 2017).

### 4. Nanofertilisation (2006–2015):

Nanotechnology offered a fundamentally different toolkit, with engineered particles such as zinc oxide, titanium dioxide, and iron oxide tested as carriers that deliver nutrients with far greater precision, cutting runoff losses while improving root absorption (Raliya et al., 2015).

### 5. Nanofortification (2016–present):

The focus has since shifted from feeding the plant to enriching the food it produces for human consumption. Nanoencapsulated vitamin B-complex and folic acid carriers have demonstrated markedly improved stability and delivery (Rathee et al., 2022), and cerium and manganese-based nanocomposites have been reported to noticeably increase shoot growth and biomass in wheat (Zarinkoob et al., 2021).

## Nanofortification vs. Conventional Fortification

Table 1. Key comparative differences between conventional fortification and nanofortification across agronomic and environmental parameters.

| Parameter            | Conventional Fortification            | Nanofortification                             |
|----------------------|---------------------------------------|-----------------------------------------------|
| Nutrient Release     | Immediate, bulk application           | Controlled, sustained release                 |
| Bioavailability      | Often low; prone to fixation/leaching | High; enhanced by nanoscale surface area      |
| Uptake Efficiency    | Typically below 50%                   | Significantly higher; targeted delivery       |
| Environmental Loss   | High; leaching and runoff common      | Reduced through controlled release            |
| Development Timeline | Rapid (mass) to very slow (breeding)  | Moderate; formulation-dependent               |
| Cost to Producer     | Low to moderate                       | Currently higher; expected to fall with scale |

## Why Nanofortification Matters: Drivers and Benefits

**A. Combating Hidden Hunger:** India continues to rank poorly on global hunger indices even while

producing enormous volumes of staple grain, a paradox rooted in micronutrient shortfalls rather than caloric ones. Enriching rice and wheat with zinc, iron, and selenium at the point of cultivation offers a



way to reach gaps that supplementation programmes alone often miss (Ritchie et al., 2018).

### **B. Building Resilience Against Climate Stress:**

Unpredictable monsoons, rising temperatures, and more frequent dry spells have already begun eroding yields across India's farming regions (Mall et al., 2017). Crops treated with nanoscale nutrient carriers show a greater capacity to sustain photosynthesis and nutrient transport under such stress.

**C. Improving Nutrient Use Efficiency:** Ordinary nitrogen fertiliser is strikingly inefficient only a third to two-fifths of what is applied is absorbed by the crop (Chen and Yada, 2011). Nanoscale carriers can be engineered to release nutrients more gradually and precisely, an advantage that matters most for micronutrients like zinc and iron.

**D. Meeting Demand for Safe, Nutrient-Dense Food:** Consumers increasingly want food that is measurably nutritious and free of unnecessary chemical residue a combination nanofortification is well placed to deliver.

**E. Enabling Sustainable Intensification:** For a country producing rice, wheat, and pulses at India's scale, raising output without further straining soil and water resources is now a policy necessity. Nanofortification supports this by improving nutrient cycling and lowering dependence on bulk chemical inputs (Kah et al., 2019).

**F. Institutional and Policy Momentum:** Research institutions such as ICAR and IARI have already moved beyond laboratory-stage interest, and commercially available products such as Nano Urea show that nanotechnology-driven nutrient delivery has genuinely reached Indian farms.

Beyond these broader drivers, nanofortification also delivers tangible agronomic outcomes: higher nutrient-absorption efficiency thanks to the large surface area of nanoparticles relative to their size, improved yield and grain nutrient density in field

trials, and greater tolerance to drought, salinity, and heavy-metal exposure. Encouragingly, at properly optimised concentrations these gains come without the phytotoxic effects that might otherwise be expected from introducing engineered materials into a living system (Ma et al., 2010).

### **Methods of Delivering Nanofortification**

Several complementary techniques have been developed to deliver nanoscale nutrients to crops, each suited to different crop types, soils, and growing conditions (Raliya et al., 2015).

**1. Foliar Application:** Spraying a nanoparticle suspension directly onto leaves, where it is absorbed quickly through stomatal pores. Bypassing the soil this way tends to act faster than root-based methods and has been used to deliver micronutrients such as zinc and selenium to field crops.

**2. Soil Application:** Introducing nanoparticles into the root zone for gradual release over time a profile that suits fields affected by drought or heavy-metal contamination, where a steady nutrient supply matters more than a rapid one.

**3. Nano-enabled Biofortification:** Applying selenium, iodine, or copper nanoparticles under nutrient-poor or hydroponic conditions to raise the nutritional value of crops that would otherwise struggle to accumulate these elements.

**4. Nanoencapsulation:** Wrapping a nutrient inside a protective nanoscale shell, shielding it from degradation and allowing controlled rather than immediate release useful for nutrients that are unstable or prone to leaching.

**5. Seed Priming:** Treating seeds with nanoparticles before sowing to improve germination, strengthen early seedling growth, and prime the plant's antioxidant defences ahead of later stress.

**6. Root Dipping and Hydroponic Enrichment:** Dipping roots in a nanoparticle solution before



transplanting, or dissolving nanoparticles into a hydroponic nutrient solution, for uniform delivery without soil-related losses.

**7. Nanoparticle-Coated Fertilisers:** Coating conventional fertiliser granules with a thin nanoparticle layer to improve macro- and micronutrient delivery while reducing the overall quantity of fertiliser needed.

### Case Studies: Evidence from Wheat and Rice

**Case Study 1: Ce-Mn Ferrite Nanocomposites in Wheat:** The first study centres on wheat treated with a specially engineered cerium-manganese (Ce-Mn) ferrite nanocomposite, roughly 88 nanometres across and structured as a cubic spinel. Seeds exposed to this material at 100 and 250 parts per million germinated at rates around 15 percent higher than untreated controls, developed shoots up to 44 percent longer, and accumulated as much as 92 percent more biomass. Photosynthetic pigments rose in step total chlorophyll increased by 61 percent and carotenoids by 38 percent at the lower dose while the plants' internal antioxidant enzymes, including catalase and superoxide dismutase, became more active, a sign that the seedlings were coping well with the added material rather than being stressed by it. That picture changed sharply at 500 ppm: germination and root length both fell, and markers of cellular damage such as malondialdehyde climbed noticeably. The lesson from this trial has less to do with the nanoparticle itself than with dosage iron and manganese remain valuable cofactors for photosynthesis and enzyme function only within a fairly narrow concentration band, beyond which the same material that nourished the plant begins to harm it (Zarinkoob et al., 2021).

**Case Study 2 – Green-Synthesised ZnO Nanoparticles in Rice:** The second study takes a different route to sustainability, growing its own nanoparticles from a brown seaweed extract rather than synthesising them through conventional industrial chemistry. Zinc oxide particles produced

this way, measuring between 30 and 50 nanometres, were tested across two full growing seasons of field trials on rice in Egypt, applied as a foliar spray either alone or alongside standard zinc sulphate fertiliser. The combined treatment consistently outperformed zinc sulphate alone: chlorophyll readings reached just over 40 SPAD units, plants grew to more than 94 centimetres in height, and panicle weight, closely tied to eventual grain yield, rose by roughly a third. The nutritional payoff was equally clear, with zinc accumulation in the harvested grain increasing by nearly 32 percent and nitrogen content rising by more than 30 percent. The one exception was phosphorus, which dipped slightly at the highest nanoparticle doses, a reminder that even a broadly beneficial treatment can create trade-offs elsewhere in a plant's nutrient balance (Elshayb et al., 2021).

### Challenges and Limitations

For all its promise, nanofortification carries genuine limitations that deserve honest treatment. Its benefits are tightly bound to dosage, and as both case studies show, the gap between a concentration that nourishes and one that harms can be surprisingly narrow. Far less is understood about how these engineered particles behave over longer timeframes, their interaction with soil microbial communities, and where they ultimately end up in the wider environment. The more sophisticated delivery methods, such as nanoencapsulation and hydroponic enrichment, remain costly and technically demanding compared with conventional fertilisation, which could limit their reach among the smallholder farmers who stand to benefit most. Regulatory frameworks for engineered nanomaterials in agriculture are still being written in most countries, and consumer comfort with nano-treated food remains largely untested.

### Conclusion

Nanofortification is best understood not as a sudden breakthrough but as the latest step in a century-long



effort to put nutrients back where diets and soils have lost them, building on mass fortification, agronomic biofortification, and genetic breeding, but achieving a precision none of those earlier stages could match. The wheat and rice studies reviewed here make the same point from two directions: get the dose right, and nanoparticles can measurably improve germination, biomass, photosynthetic efficiency, and grain nutrient content; get it wrong, and the same tool can just as easily cause harm. Turning that promise into dependable practice will take further field testing, careful dosage calibration, and regulatory frameworks built to keep pace with the science work that could make nanofortification a genuinely practical answer to hidden hunger.

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# Engineering the Future of Food: Gene Editing versus Genetic Modification

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The world's population is projected to reach 10 billion people by 2050 and climate change is putting increasing pressure on the productivity of crops. The demand for resilient, high-yield and nutritious crops is now greater than ever, and the world is looking into 10 billion people by 2050, as climate change is increasing the pressures on crop productivity. Today's farmers are dealing with an increasing number of problems, such as changing weather patterns, new pests and diseases, dwindling land, and the increasing demands to produce more on less land and with less natural resources. These issues are making agriculture increasingly dependent on traditional crop improvement and there is an urgent need for more rapid and accurate breeding technologies.

Biotechnology is changing the crop development process. Scientists can now modify desirable traits with unprecedented precision and efficiency, from genetically modified (GM) crops to new gene editing technologies that are based on CRISPR. Though both technologies are focused on bolstering food security and sustainability, they have distinct approaches, applications, and public perception. Learning about these innovations is critical to the future of farming and the engineering of food in a changing world.

## The Evolution of Crop Improvement

Since the dawn of agriculture, more than 10,000 years ago when man learned to cultivate plants, crop improvement has been the central theme of agricultural research. Early farmers would choose the best plants of the most healthy and productive, and the most hardy plants, and improve the crops by choosing them for their better traits. The process gradually became established as traditional plant breeding where various desirable characteristics like yield, disease resistance and quality were sought in the seeds produced by controlled crossbreeding. Conventional breeding is very successful, but it is also time consuming, depending on the occurrence of natural variation in the plant or animal and multiple generations.

With the advent of molecular biology, crop improvement was revolutionized because it allowed scientists to understand and manipulate the genome of plants with better precision. In the 1990s we saw a big step forward in the genetic modification of crops

(GM), whereby desirable genes were transferred from the same or another species for insect resistance or herbicide tolerance. More recently, a new wave in precision breeding has been introduced with the gene editing technology, especially the CRISPR-Cas9 system, allowing targeting of a plant's own genes without the need for foreign gene insertion. This path from selective breeding to molecular breeding has given agriculture some great tools to create crops that are resilient, productive, and nutritious, to support a changing world.

## The Rise of Genetically Modified Crops:

Genetically Modified (GM) crops were introduced in the 1990s, which led to a turning point in agricultural biotechnology. In contrast to traditional breeding, where desirable traits are repeatedly introduced by crossing different plant varieties, genetic modification enables scientists to transfer specific genes into a plant's genome, even from entirely different organisms to provide the plant with new desirable features. The breakthrough has paved the



way for crops that are resistant to insects, tolerant to herbicides, nutritionally superior, and better able to tolerate environmental stresses.

In several cropping systems, GM technology has played an important role in agriculture by lowering the use of chemical pesticides, reducing crop losses, and increasing productivity in the global picture. Some of these are well known, such as Bt cotton, which produces the protein that kills certain insect pests, Bt maize, herbicide-tolerant soybean, and Golden Rice, which is developed to overcome vitamin A deficiency. While these successes have been achieved, GM crops also have been the subject of discussions on biosafety, environmental effects, IP rights, and consumer acceptance. However, they laid the groundwork for today's crop biotechnology and helped set the stage for the development of more sophisticated genome editing tools.

### Precision Gene Editing: Redefining Agriculture:

Gene editing has become one of the most promising advances in agricultural biotechnology, offering the opportunity to modify the agrobiodiversity's own genome in a targeted and precise manner without the need for the introduction of foreign genes. The CRISPR-Cas9, TALENs and Zinc Finger Nucleases (ZFNs) are examples of technologies that can precisely target and delete, replace, or modify desired DNA sequences, sometimes referred to as "molecular scissors". This precision makes it possible for plant breeders to create new, more precise crop varieties in a matter of just a few years, rather than the many years of conventional breeding.

In gene editing, the genes of the plant are modified, but not necessarily transferred from another organism, unlike in genetic modification. The application of the technology is being researched to create pest and disease resistant crops, drought, heat, and salinity resistant crops, nutritious crops, durable shelf-life crops, and efficient crops for the use of resources. In the recent years, breakthroughs in the

development of gene-encoded tomatoes with added gamma-aminobutyric acid (GABA), disease resistant wheat and climate resistant rice varieties have been made. With regulatory changes and increasing acceptance, gene editing is quickly becoming an integral part of precision breeding, providing sustainable solutions to enhance food security while reducing environmental impact.

### Gene Editing vs. Genetic Modification: What's the Difference?

| Feature                     | Genetic Modification (GM)                                 | Gene Editing                                                               |
|-----------------------------|-----------------------------------------------------------|----------------------------------------------------------------------------|
| <b>Genetic change</b>       | Introduces foreign DNA from the same or different species | Modifies the plant's existing DNA                                          |
| <b>Precision</b>            | High                                                      | Very high                                                                  |
| <b>Development time</b>     | Longer                                                    | Shorter                                                                    |
| <b>Cost</b>                 | Relatively high                                           | More cost-effective                                                        |
| <b>Foreign DNA</b>          | Usually, present                                          | Often absent                                                               |
| <b>Primary applications</b> | New traits (e.g., insect resistance, herbicide tolerance) | Trait improvement (e.g., drought tolerance, disease resistance, nutrition) |
| <b>Examples</b>             | Bt cotton, Golden Rice                                    | GABA tomato, disease-resistant wheat, climate-resilient rice               |
| <b>Regulatory</b>           | Generally,                                                | More flexible in                                                           |



|                          |                    |                                               |
|--------------------------|--------------------|-----------------------------------------------|
| <b>approach</b>          | more stringent     | several countries for non-transgenic products |
| <b>Public perception</b> | More controversial | Generally viewed more favourably              |

### Beyond the Debate: Are They Competitors or Partners?

Gene editing and genetic modification is often seen as a technological competition, but this isn't the case, and each technique has its own specific applications. Genetic modification has been especially useful for the addition of new traits from other organisms, for example insect resistance or improved nutrient profile, which cannot be accomplished by traditional breeding methods. In contrast, gene editing does very well at improving existing traits in the plant's own genome, thus creating superior climate-resistant, disease-resistant, and high-yielding crop varieties.

Both technologies will be important tools for crop improvement in the future, as agriculture strives to meet the challenges of food security and environmental sustainability. They aren't mutually exclusive; they are complementary resources for breeders to overcome a wide range of production issues. The combination of conventional breeding, GM and gene editing will likely be the method of the future, as a more integrated approach is needed to create crops that are more productive, climate resistant, nutritious and resilient.

### The New Wave of Innovation:

| Crop Variety / Event Name | Modification Type     | Key Target Trait & Breakthrough                                             | Primary Source of Information           |
|---------------------------|-----------------------|-----------------------------------------------------------------------------|-----------------------------------------|
| <b>DRR Dhan 100 (Kam)</b> | Gene Edited (CRIS PR- | <b>High Yield &amp; Early Maturity:</b> Knocks out the native <i>OsCKX2</i> | Indian Council of Agricultural Research |

|                               |                             |                                                                                                                                                                                     |                                                                                      |
|-------------------------------|-----------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------|
| <b>ala) (Rice)</b>            | Cas9)                       | gene to deliver a 25% yield increase and a 15–20 day faster maturity cycle.                                                                                                         | (ICAR) Institutional Launch / Healthy Crops Consortium                               |
| <b>Pusa DST Rice 1 (Rice)</b> | Gene Edited (CRIS PR- Cas9) | <b>Salinity &amp; Drought Tolerance:</b> Delivers up to a 30.36% higher yield under intense saline stress, performing robustly in degraded and water-limited soils.                 | Indian Council of Agricultural Research (ICAR) Release / Times Agriculture           |
| <b>GAB A Tomato</b>           | Gene Edited (CRIS PR)       | <b>Nutritional Enhancement:</b> The world's first commercial CRISPR food item, edited to accumulate high levels of gamma-aminobutyric acid (GABA) to aid blood pressure management. | Japan Ministry of Health, Labour and Welfare / Seed Sector Commercialization Reports |
| <b>TELA Maize Hybrids</b>     | Genetic Modification (GM)   | <b>Drought Tolerance &amp; Insect Resistance:</b> Transgenic stacked protection lines approved commercially for direct human food supply in East Africa.                            | Ethiopian Agricultural Authority / Plantae Biotech Regulatory Review                 |
| <b>Nema sphere (Soybean)</b>  | Genetic Modification (GM)   | <b>Soybean Cyst Nematode (SCN) Resistance:</b> Uses a novel transgenic <b>Cry14 protein</b> that targets and disrupts the internal nutrient                                         | BASF Agricultural Solutions Commercial Trait Pipeline                                |



|                                      |                            |                                                                                                                                                                     |                                                                                      |
|--------------------------------------|----------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------|
|                                      |                            | absorption of root nematodes.                                                                                                                                       |                                                                                      |
| <b>High-Lodging Resistant Barley</b> | Gene Edited (CRIS PR-Cas9) | <b>Structural Rigidity:</b> Knocks out the <i>HvGS3</i> gene to engineer semi-dwarf barley, achieving a <b>76.6% increase</b> in the Culm Lodging Resistance Index. | <i>Plant Biotechnology Journal</i> / Peer-Reviewed Research Archive                  |
| <b>Reduced-Gluten Wheat</b>          | Gene Edited (CRIS PR)      | <b>Allergen Reduction:</b> Precision deletion of a cluster of specific native genes responsible for producing celiac-triggering immune-reactive gluten proteins.    | University of California, Davis (UC Davis) / <i>Theoretical and Applied Genetics</i> |

### Innovation with Responsibility: Regulations, Ethics, and Public Trust

With the progress of agricultural biotechnology, scientific innovation needs to be supported by a solid regulatory framework and public trust. Different countries have different ways of regulating GM and gene edited crops due to their different priorities on food safety, environment and innovation. Although genetically modified (GM) crops are typically required to be subject to extensive biosafety testing and approval procedure, there are some countries that have implemented more flexible regulations for some gene edited crops that do not contain foreign DNA. Science-based policies are still crucial to promote the safe and responsible development and use of these technologies.

In addition to regulations, ethical issues and public opinion are important aspects in the

acceptability of biotechnology. Public debate remains on issues of food safety, biodiversity, IP rights, labelling and access to food. Open dialogue, scientific assessment and the participation of relevant stakeholders can help build trust between farmers, consumers, researchers and policy-makers in addressing these challenges. Finally, the potential of agricultural biotechnology for success in the long term will rely not just on scientific advances, but also on responsible governance and a participative public.

### Conclusion: Engineering Food for a Changing World

It is not a question of choosing gene editing over genetic modification, it is about leveraging the best of both worlds to tackle the 21st century's big agriculture challenges. Gene Editing is significantly more precise and rapid than GM, and has the potential to introduce new traits, whereas, GM only has the potential to introduce new traits. When combined, these technologies are opening up a new range of plant breeding opportunities to create crops with greater climate change resilience, pest and disease resistance, nutritional improvements, and adaptation to sustainable farming practices.

With ever less natural resources and an evolving climate, agricultural biotechnology will be vital to future food systems as the world's demand for food grows. But there must be regulations, ethics and trust in scientific innovation. Instead of a conflict between "gene editing" and "genetic modification," we want to focus on one shared objective—designing a future in which agriculture is viable, sustainable and able to feed future generations.

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## Methane Credits: A New Frontier for Climate Resilience and Farmers Livelihoods

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Methane is a major greenhouse gas emitted from rice cultivation and livestock, significantly contributing to climate change. This article highlights the concepts of methane credits as an emerging opportunity for farmers to earn additional income by adopting climate-smart agricultural practices such as System of Rice Intensification (SRI) and Integrated Nutrient Management (INM). It also explains the role of satellite monitoring, digital technologies and carbon markets in verifying methane emission reductions. Global developments and India's future roadmap for methane credit implementation for sustainable agriculture while contributing to climate resilience and environmental conservation

### Did You Know?

- Methane is 28-34 times more powerful than CO<sub>2</sub> in warming the atmosphere over 100 years.
- Rice cultivation and livestock are the two largest agriculture sources of methane.
- Reducing methane is one of the fastest ways to slow global warming.
- Farmers may soon be able to earn income through verified methane reductions.

Agriculture is the backbone of food security, but it is also one of the largest contributors to greenhouse gas emission. Among these gases, methane (CH<sub>4</sub>) has emerged as a major concern because of its strong impact on global warming. According to the Intergovernmental Panel on Climate Change (IPCC), methane has a Global Warming Potential (GWP) 28-34 times greater than carbon dioxide (CO<sub>2</sub>) over a 100 year period, meaning that even relatively small quantities of methane can significantly increase global where oxygen deficient conditions promote anaerobic decomposition, and from enteric

fermentation in livestock, where microorganisms in the decomposition, and from enteric fermentation in livestock, where microorganisms in the digestive system release methane during feed digestion. Together, rice cultivation and livestock account for a substantial share of agricultural greenhouse gas emission worldwide.

As countries strive to achieve climate goals and reduce greenhouse gas emissions, agriculture is increasingly being viewed not only as part of the problem but also as a important part of the solution. Improved farming practices can substantially reduce methane emission while maintaining productivity and conserving natural resources. More importantly, these reductions can now be translated into economic benefits through the emerging concept of methane credits. Similar to carbon credits, methane credits reward verified reduction in methane emissions, creating a new opportunity for farming to earn supplementary income while contributing to climate change mitigation. With advance in digital monitoring, satellite technology, and environmental markets, methane credits have the potential to





become an important component of climate-smart agriculture in the coming years

### What is Methane (CH<sub>4</sub>)?

Methane (CH<sub>4</sub>) is a colourless, odourless and highly flammable greenhouse gas that occurs naturally and is also produced through human activities. It is formed when organic matter decomposes in oxygen-deficient conditions. Although methane remains in the atmosphere for only about 12 years, it has a much strong warming effect than carbon dioxide. According to the IPCC, methane has a Global Warming Potential (GWP) 28-34 times higher than CO<sub>2</sub> over a 100-year period and about 80 times higher over 20 years. This makes methane one of the most atmospheric greenhouse gases responsible for accelerating climate change. Globally, atmospheric methane concentrations have increased rapidly due to agriculture, fossil fuel production, waste management and other human activities. Because methane has a relatively short atmospheric lifetime, reducing its emission can produce rapid climate benefits, making methane mitigation one of the fastest strategies to slow warming.

### Why is Methane Dangerous?

Methane is considered one of the most harmful greenhouse gases because of its exceptionally high heat trapping capacity. Increased methane emission contributes significantly to global warming, causing rising temperatures, unpredictable rainfall, frequently droughts, floods and heat waves that directly affect agricultural productivity. Methane also reacts with atmospheric pollutants to form ground level ozone, which damages crops, reduces crop yields and affects human health by causing respiratory diseases. Scientific studies indicate that reducing methane emission is one of the quickest ways to reduce the rate of climate change. According to the United Nations Environment Programme (UNEP), reducing global methane emission by 45%

before 2030 could avoid nearly 0.3°C of global warming by 2045. Therefore, methane reduction not only protects the environmental but also strengthens food security, improves public health and supports sustainable agriculture development.

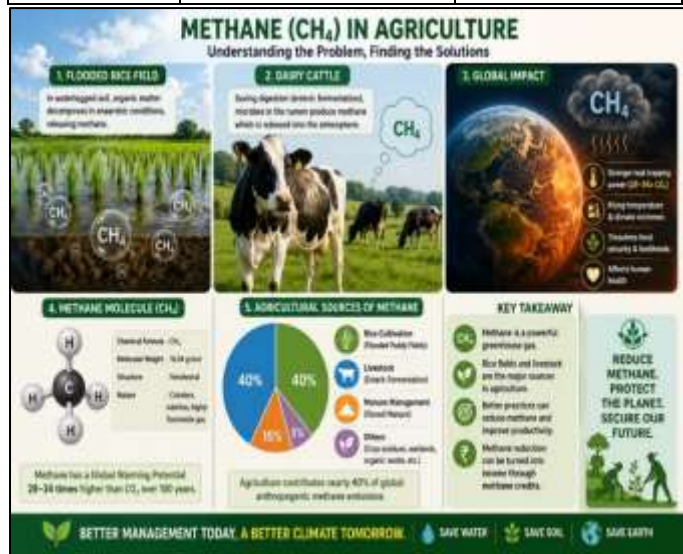
### Major Sources of Methane in Agriculture:

Agriculture contributes nearly 40% of global anthropogenic methane emissions, with rice cultivation and livestock production being the largest sources. In flooded rice fields, continuous waterlogging creates anaerobic soil conditions where microorganisms decompose organic matter and release methane into the atmospheric. Livestock such as cattle, Buffaloes, sheep and goat emit methane during digestion through a natural process known as enteric fermentation. Animal manure stored anaerobic conditions also produce methane during decomposition. Additional agriculture sources include organic waste, crop residues and wetlands associated with farming systems. Since this emission originate from biological processes, adopting improved agriculture practices such as System of Rice Intensification (SRI), Alternate Wetting and Drying (AWD), Integrated Nutrient Management (INM), improved livestock feeding and biogas production can substantially reduce methane emission while maintaining agriculture productivity.

| Source                         | How Methane is Produced                   | Mitigation Option                   |
|--------------------------------|-------------------------------------------|-------------------------------------|
| Flood Rice Feilds              | Anaerobic decomposition of organic matter | SRI, AWD, Proper water management   |
| Livestock (Cattle and Buffalo) | Enteric fermentation during digestion     | Improved feed quality and additives |
| Animal Manure                  | Anaerobic decomposition during storage    | Composting, biogas plants           |



|                           |                                    |                                   |
|---------------------------|------------------------------------|-----------------------------------|
| Crop Residues             | Decomposition under wet conditions | Residue management and composting |
| Wetlands and Marshy Areas | Natural anaerobic decomposition    | Wetland management                |



## 1. System of Rice Intensification (SRI)

The SRI is an innovative rice cultivation technique that emphasize AWD instead of continuous flooding. By allowing the soil to remain aerobic for part of the growing season, methane-producing microorganisms are suppressed, leading to lower methane emissions. SRI also promotes healthy root growth, improves water use efficiency, enhances soil microbial activity and often increases grain yield while reducing irrigation requirements.

### Benefits of SRI

- Reduces methane emissions
- Saves 25-40% irrigation water
- Improves root development
- Increases rice productivity
- Reduces production costs

## 2. Integrated Nutrients Management (INM)

INM combines organic manures, crop residues, biofertilizers and balanced chemical/organic fertilizers to improve soil fertility while minimizing greenhouse gas emissions. Proper nutrient management reduces excessive anaerobic decomposition and enhances microbial balance, leading to 40-60% lower methane emission compared with traditional nutrients management. INM also improves soil health, increases nutrient use efficiency and supports long term agricultural sustainability.

### Benefits of INM

- Reduces methane formation
- Improves soil organic matter
- Enhances nutrients efficiency
- Increases crop productivity

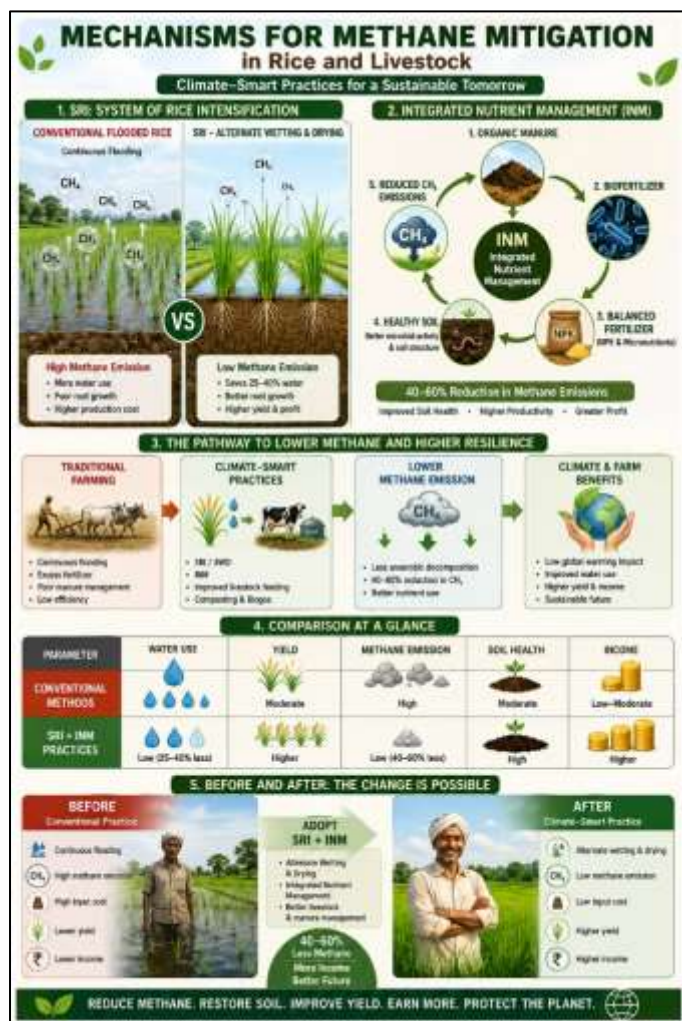
## Mechanisms for Methane Mitigation in Rice and Livestock:

### Reducing methane through climate-smart agricultural practices

Methane emissions from agriculture can be significantly reduce through the adoption of climate-smart farming practices that improves productivity while minimizing environmental impacts. Two of the most promising approaches are the SRI and INM. These practices reduce anaerobic conditions in the soil, improvement nutrients-use efficiency and decrease methane formation without compromising crop yield. Studies indicate that combining improved water management, balanced fertilization and sustainable residue management can reduce methane emission by 40-60%, making these practices important tools for climate change mitigation and sustainable agriculture.



- Promotes sustainable farming



can be converted into credits that are sold to industries, corporations or governments seeking to offsets their greenhouse gas emissions. This creates a new revenue stream while encouraging sustainable farming practices and supporting national climate goals.

## How does this process work?



## Carbon Market Participation and the Future of Methane Credits:

### Carbon Market Participation: Turning Emission Reductions into Farmer Income

Climate change mitigation is no longer only an environmental responsibility it is becoming an economic opportunity. Through methane credit mechanisms, farmers who adopt climate smart agricultural practices such as the system SRI, INM, improved livestock feeding and better manure management can reduce methane emissions and potentially earn additionally income. Similar to carbon credits, methane credits are tradable environmental assets. Once emission reduction is scientifically measured, verified and certified they

## Global Progress in Methane Credits:

Several countries have already integrated methane reduction into climate policies and environmental markets. The United States supports methane reduction through livestock management, rice cultivation projects and voluntary carbon markets. Australia promotes carbon farming initiatives where livestock producers receive incentives for reducing methane emissions. New





Zealand is investing in methane reducing livestock technologies because agriculture contributes significantly to its national greenhouse gas emissions. Countries within the European Union are encouraging sustainable agricultural practices through climate smart policies and financial incentives as both an environmental necessity and an economic opportunity.

### India's Roadmap Towards Methane Credits:

India has not yet established a dedicated methane credit market for farmers, but several initiatives indicate positive progress. The Carbon Credit Trading Scheme (CCTS), National Mission for sustainable Agriculture, Digital Agriculture Mission and increasing use of remote sensing and satellite technologies are laying the foundation for future climate finance mechanisms. Experts anticipate that methane credit opportunities could emerge during the late 2020s and early 2030s, particularly in rice growing regions, dairy farming watershed development programs and Farmers Producers Organizations (FPOs). Initially, participation is expected through community-based projects to reduce monitoring and certification costs. Strengthening governance, digital monitoring systems and farmers awareness will be essential for enabling smallholders to access these emerging environmental markets.

### Conclusion:

Methane emission from rice cultivation and livestock are among the largest agricultural contributors to climate change, but they also present a unique opportunity for farmers to participate in the emerging green economy. Climate-smart practices such as SRI and INM not only reduce methane emission by improving soil and water management but also enhance crop productivity, conserve natural resources and strengthen farm resilience. As global carbon markets continue to expand, methane credits have the potential to provide farmers with an

additional source of income while rewarding sustainable agricultural practices. Although India is still developing its methane credits framework, advances in digital monitoring, satellite technology and supportive government policies indicates promising opportunities in the coming years. Increasing awareness, promoting farmers participation through FPOs and strengthening scientific monitoring system will be essential to ensure that Indian agriculture benefits from future methane credit markets.

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# Actinorhizal Symbiosis: An Enigmatic Nitrogen Fixer

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Actinorhizal symbiosis refers to a mutualistic relationship between the actinobacterium *Frankia* and the roots of woody dicotyledonous plants, spanning 25 genera across eight different families. This partnership culminates in the development of coralloid root nodules, which facilitate the conversion of atmospheric nitrogen into forms that are readily usable by plants. This process enables plant growth in soils that are deficient in nitrogen or have been degraded. Actinorhizal plants serve as efficient pioneer species for activities such as land reclamation, reforestation, and phytoremediation, especially in the presence of abiotic stresses including drought, salinity, and heavy metal contamination. The process of infection by the nitrogen-fixing actinobacterium *Frankia* occurs via the invasion of root hairs or through intercellular pathways, varying with the specific host plant involved. Actinorhizal nodules, while akin to legume nodules, originate from distinct developmental pathways and demonstrate unique patterns of gene expression. Recent genomic investigations have uncovered intricate signalling mechanisms and specificity within these systems, underscoring their potential role in promoting sustainable land management practices and facilitating ecosystem restoration efforts.

## 1. The Role of *Frankia* in Actinorhizal Symbiotic Relationships

The genus *Frankia* includes filamentous actinobacteria that can establish nitrogen-fixing symbiotic relationships with various woody dicotyledonous plants, known collectively as actinorhizal species. In both culture and in their symbiotic form, *Frankia* develops into three different cell types: vegetative hyphae, nitrogen-fixing vesicles, and multilocular sporangia.

Vesicles, which serve as the main location for nitrogenase activity, are encased in multilayered envelopes that are abundant in hopanoids. These structures function as barriers for gas diffusion, facilitating nitrogen fixation even in aerobic environments. This characteristic distinguishes *Frankia* from rhizobia, the latter primarily being obligate symbionts that do not perform free-living nitrogen fixation. Additionally, *Frankia* strains exhibit variability in their ability to sporulate, with spore-forming strains (spore<sup>+</sup>) generally showing

enhanced infectivity compared to non-sporulating strains (spore<sup>-</sup>). Molecular techniques, including 16S rRNA and *nif* gene markers, have uncovered considerable genetic variation within the genus, aiding in phylogenetic classification and studies of host specificity. Despite their slow growth and genetic complexity, *Frankia* species can survive in soil environments lacking actinorhizal hosts and exhibit nitrogen-fixing capabilities in non-symbiotic associations, suggesting they have ecological functions that extend beyond symbiotic relationships. As genomic and molecular tools continue to develop, *Frankia* remains a key model organism for researching nitrogen fixation, microbial adaptation, and sustainable ecological restoration practices.

## 2. Structure and gene expression in actinorhizal plants

Actinorhizal root nodules are structures that grow indefinitely and resemble lateral roots, but they develop independently and do not form a root cap. These nodules consist of several distinct regions,

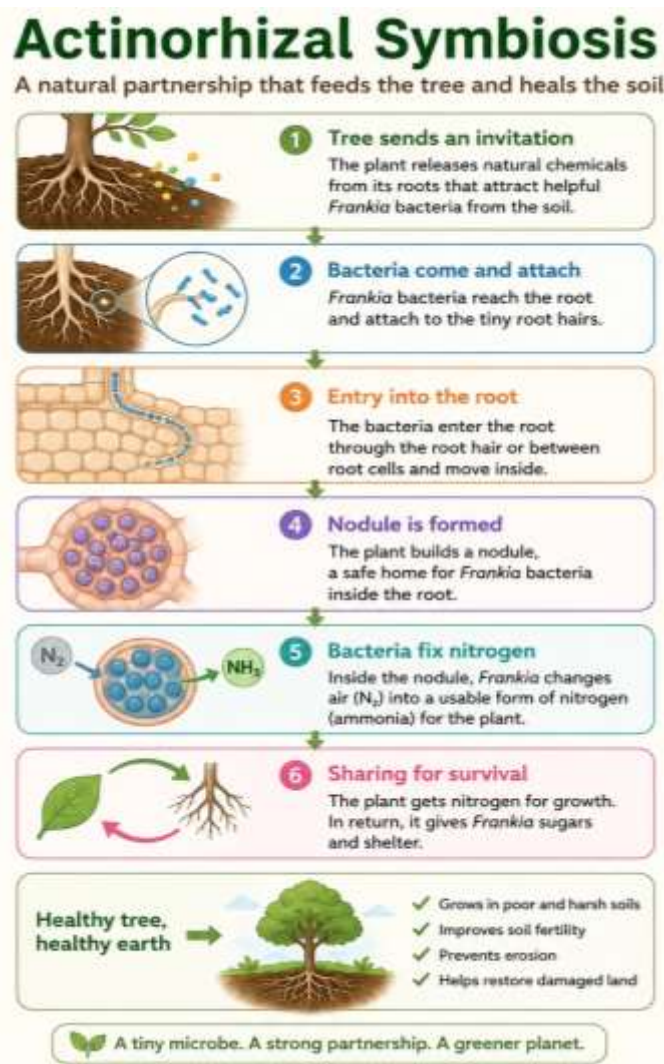




including an apical meristem, an infection zone, a nitrogen fixation zone, and a senescent zone. Within the nitrogen fixation zone, there are both infected cells containing nitrogen-fixing vesicles and uninfected cells that participate in nutrient exchange. The anatomical structure of nodules and the mechanisms for protecting oxygen differ among genera. Studies of gene expression have identified both unique genes and those homologous to legume genes, such as early nodulins and hemoglobins, suggesting that certain functions are conserved. These insights strengthen the evolutionary connections between actinorhizal and legume symbioses, highlighting distinct developmental pathways that are regulated independently.

### 3. Infection pathways in actinorhizal symbiosis

In actinorhizal symbioses, *Frankia* establishes infection through either intracellular or intercellular methods, which vary depending on the specific lineage of the host plant. In plants belonging to the order Fagales, the infection primarily occurs intracellularly. This process begins with the deformation of root hairs, allowing bacterial entry through a curled structure similar to that seen during rhizobial infections in legumes. Conversely, in members of the Rosales and potentially Cucurbitales, *Frankia* adopts an intercellular pathway, accessing the root cortex by enzymatically breaking down the middle lamella that separates adjacent epidermal cells. Once the bacteria penetrate the host, they differ from rhizobia by remaining within specialized plant-derived fixation threads rather than being released into the cytoplasm. Inside these threads, *Frankia* differentiates into specialized nitrogen-fixing vesicles, which create a low-oxygen environment necessary for optimal nitrogenase function. These differing infection mechanisms highlight the evolutionary adaptability of actinorhizal symbiosis and illustrate its unique modifications across various plant lineages.



### Steps Involved in Actinorhizal Symbiosis

#### 4. Ecological benefits of Actinorhizal symbiosis

- Frankia* convert inert nitrogen gas ( $N_2$ ) into ammonia, thereby enhancing nitrogen levels in the surrounding ecosystem.
- Actinorhizal plants, including species such as Alders and Casuarina, serve as pioneering organisms on barren and disturbed landscapes, including volcanic flows, sand dunes, and landslide areas, by progressively enriching the soil with organic matter.
- These actinorhizal plants exhibit rapid growth in harsh conditions, and their extensive root



systems contribute to the stabilization of loose soil.

4. Actinorhizal plants have the capacity to sequester heavy metals within their tissues, while *Frankia* possesses the ability to biodegrade toxic aromatic hydrocarbons, enabling plants to thrive in environments affected by salinity or elevated heavy metal concentrations.

5. The actinorhizal symbiotic relationship facilitates robust growth in woody trees and

shrubs, leading to substantial biomass accumulation, which contributes to the reduction of greenhouse gases through enhanced atmospheric CO<sub>2</sub> absorption.

6. The accumulation of dense leaf litter and the extensive root development linked to actinorhizal flora enhance soil structure, which increases the soil's moisture retention capabilities and lowers the localized water table in waterlogged conditions.

### Important Actinorhizal Plants and Their Ecological Advantages

| Family        | Associated trees/shrubs                                      | Environmental Application                                 |
|---------------|--------------------------------------------------------------|-----------------------------------------------------------|
| Betulaceae    | <i>Alnus glutinosa</i> , <i>A. incana</i>                    | Accumulate heavy metal, break hexachlorocyclohexanes      |
| Casuarinaceae | <i>Casuarina equisetifolia</i>                               | Soil stabilization and carbon sequestration               |
| Coriariaceae  | <i>Coriaria myrtifolia</i>                                   | Biomonitoring and erosion control                         |
| Dastiscaceae  | <i>Datisca glomerata</i>                                     | Soil fertility reclamation and erosion control            |
| Elaeagnaceae  | <i>Elaeagnus angustifolia</i>                                | Saline-alkali soil reclamation, heavy metal biomonitoring |
| Myricaceae    | <i>Myrica gale</i> , <i>M. cerifera</i>                      | River bank stabilization, invasive species management     |
| Rhamnaceae    | <i>Ceanothus americanus</i> , <i>D. trinervis</i>            | Pollinator support and fire management                    |
| Rosaceae      | <i>Purshia tridentata</i> ,<br><i>Cercocarpus ledifolius</i> | Land reclamation and erosion control                      |

### 5. Conclusion

Actinorhizal plants represent a promising avenue for advancing sustainable agriculture through their capacity for nitrogen fixation in non-leguminous

species. Future research should prioritize species that are closely related and possess economic significance. While some investigations indicate synergistic interactions among *Frankia*, mycorrhizal fungi, and various other microbes, the findings



remain inconsistent. Notably, the nodulation process involving *Frankia* may also boost resistance to pathogens, thereby providing advantages that extend beyond mere nitrogen nutrition. Nevertheless, the mechanisms that govern these intricate interactions are not yet fully understood. It is crucial to conduct further foundational research to unlock the complete potential of actinorhizal symbioses for enhancing crop productivity and fostering ecological resilience.

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# Natural farming: productivity begins with the cropping system

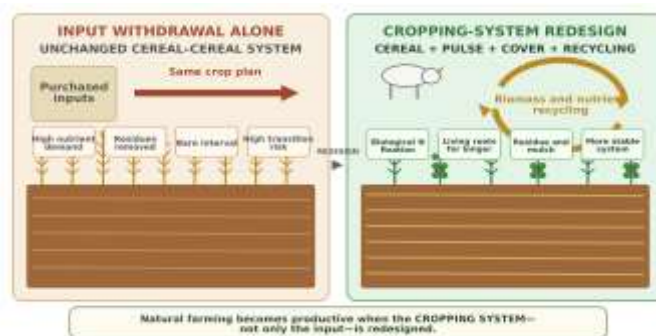
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Natural farming is often introduced as a list of preparations such as Beejamrit, Jeevamrit, mulching and botanical extracts. Yet farm productivity is decided first by the crops grown, their sequence and the amount of biomass returned to the soil. A nutrient-demanding cereal-cereal monoculture is more vulnerable during the transition because nutrient removal may exceed biological replenishment. Pulse-based rotations and intercrops usually fit better because legumes meet part of their nitrogen need through biological fixation, diversify roots and residues, keep the land productive between two main crops and spread market risk. This does not mean that cereals must be excluded. The practical route is to retain the required food-security cereal, introduce a compatible pulse in space or time, maintain soil cover, recycle residues, manage weeds early and expand natural farming only after comparing system yield, cost, profit and soil health.

The National Mission on Natural Farming, approved as a standalone Centrally Sponsored Scheme in November 2024, has placed chemical-free, ecosystem-based farming more firmly on the national agenda (Government of India 2024). The opportunity is important, but so is the need for a realistic message. Natural farming cannot be made productive merely by withdrawing fertiliser and pesticide from an unchanged crop plan. A field that has grown rice after rice, or rice followed by wheat, with residues removed and no pulse, fodder or livestock link, has a very different biological capacity from a diversified farm that keeps living roots and organic cover throughout the year.

Therefore, the first question should not be, 'Which natural formulation should I apply?' It should be, 'Which cropping system can function within the farm's biological nutrient, water and biomass budget?' Once this question is answered, the choice of seed treatment, microbial preparation, mulch and plant-protection extract becomes meaningful. The central message is simple: natural farming is most likely to succeed when the cropping system itself performs the work of nutrient cycling, soil cover, pest disruption and risk sharing.



Cereal (Wheat)

Pulse (Chickpea)

*Fig. 1. Natural farming becomes productive when biological functions are built into the cropping system*

## Natural farming is a system, not an input replacement

Natural farming is a system, not an input replacement. Replacing urea with Jeevamrit while retaining the same exhaustive monoculture is not





system change. Jeevamrit and similar preparations may stimulate biological activity, but they supply only limited quantities of crop nutrients. The harvested crop still removes nitrogen, phosphorus, potassium, sulphur and micronutrients from the field. These nutrients must come from soil reserves, crop residues, biological nitrogen fixation, farmyard manure, compost, livestock recycling, irrigation water, atmospheric deposition or other locally acceptable sources. If annual nutrient removal remains greater than replenishment, yield and soil fertility can decline over time (Kumar et al., 2020; Smith et al., 2020).

A productive natural-farming field therefore needs four biological engines: diversity of crops, continuous or frequent living roots, adequate surface cover and recycling of farm biomass. Cropping-system design determines all four. It also decides labour peaks, weed pressure, pest carry-over, moisture use and the number of marketable products obtained from one hectare.

### **Why cereal-cereal systems face a harder transition**

Cereal-cereal systems face a harder transition. Rice, wheat and maize can produce high yields, but high yields also remove large amounts of nutrients and require a strong, timely nitrogen supply. In a conventional system, fertiliser can rapidly meet this demand. In natural farming, the nutrient supply depends more heavily on mineralisation, biological nitrogen fixation and nutrient recycling, which are influenced by temperature, moisture, soil organic matter and microbial activity. Their timing may not always match the period of peak cereal demand (Smith et al., 2020).

The difficulty becomes greater when both seasons contain exhaustive cereals, crop residues are sold or burnt, the soil remains bare between crops and weeds are allowed to compete during the first 30-45 days. Heavy soils under rice-wheat may also need a

longer transition because puddling, compaction and low aeration restrict roots and biological activity. A multi-state ICAR-NAARM assessment cautioned that natural farming did not increase yields across all crops; finger millet performed better, while moderate farmyard manure improved crop performance (Kumar et al., 2020). The lesson is not that cereals are unsuitable. The lesson is that cereals must be supported by a biologically functional system rather than grown as an isolated, input-hungry crop.

### **Why pulse-based systems fit better**

Pulses are natural partners for this redesign. Through association with *Rhizobium* bacteria, a pulse crop can meet part of its own nitrogen requirement from the atmosphere. It does not provide 'free nitrogen' under all conditions: effective nodulation requires the right strain, healthy seed, suitable soil reaction, adequate phosphorus and sulphur, moisture and aeration. Even so, pulses generally depend less on external nitrogen than cereals. Their roots, nodules and residues add to a different quality of organic matter and can benefit the following crop over time (Nath et al. 2023).

Pulses also create flexible entry points. Short-duration mungbean or urdbean can be inserted after wheat and before rice or grown in rice fallows where residual moisture is available. Lentil, chickpea, and lathyrus can be sown during the winter window after rice in eastern and central India. Cowpea, greengram and pigeonpea can be intercropped with maize, pearl millet, sorghum, cotton or vegetables. These combinations diversify canopy height and rooting depth, improve land use and reduce the risk that one weather event or one price fall destroys the entire farm income.

Pulse-based does not mean pulse-only, and every pulse is not automatically suitable. A pulse selected only for its nitrogen-fixing reputation may fail if it matures too late, suffers waterlogging, competes strongly with the main crop or has no local





buyer. Pigeonpea fits many rainfed intercrops but may shade a short companion crop when duration and row ratio are poorly matched. Chickpea and lentil need drainage and timely sowing after rice. Mungbean can fit a short summer window, but delayed harvest may interfere with rice transplanting. Natural-farming design must therefore match crop duration, rooting pattern, rainfall, machinery, household use and market. The aim is functional diversity, not maximum crop count.

Long-term research in the Indo-Gangetic Plains demonstrates the soil value of pulse integration. After 16 years, rice-wheat-mungbean recorded an 8% higher soil-quality index than rice-wheat, while pulse-based systems improved available nitrogen, phosphorus and sulphur (Nath et al. 2023). These results were obtained under integrated nutrient management rather than natural farming, so they should not be presented as a direct natural-farming comparison. The relevant biological lesson is that a cereal-dominated system can gain soil-quality benefits when a pulse and organic recycling are built into the rotation.

### What field evidence is telling us

Evidence also shows why blanket statements should be avoided. Replicated trials across 28 farms in Andhra Pradesh found an overall yield advantage under zero-budget natural farming, but the response varied by crop and district. Mulch-related increases in soil moisture, lower soil temperature and greater earthworm abundance were suggested as likely mechanisms (Duddigan et al. 2023). In a 60-farmer study in Solan district, crop-equivalent yield under natural farming was 2.83-7.98% higher than under conventional farming across the reported rabi crop combinations. The largest rabi advantage occurred in a cereal-pulse combination, while cultivation costs were lower under natural farming (Laishram et al. 2022).

Field performance also depends on timely management. A poorly weeded pulse intercrop may fail even when the crop combination is sound, while a well-managed cereal-pulse system may perform strongly. The label ‘natural farming’ does not create productivity; correct crop choice, suitable plant population, timely sowing, adequate mulch, moisture conservation and early weed control do.

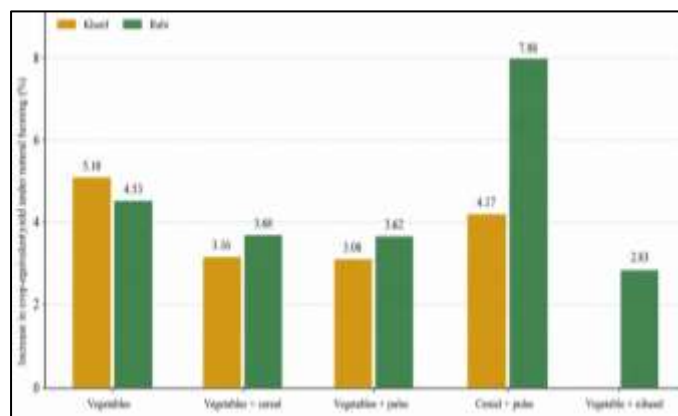


Fig. 2. Increase in crop-equivalent yield under natural farming over conventional farming in Solan district. Adapted from Laishram et al. (2022), based on a 60-farmer survey; values are location- and crop-combination-specific and should not be treated as a national average.

### Profit depends on market and labour

Profitability also depends on market and labour, not yield alone. Pulses may improve annual returns because they add a second saleable product, use a fallow window and often require less purchased nitrogen. However, a premium price for natural produce should never be assumed. Grain quality, aggregation, storage, dal processing, local demand and timely sale matter. Family nutrition and fodder value should be recorded, but they must not hide high labour demand. A useful comparison is annual net return per hectare and per day of family labour, along with crop-equivalent yield. This prevents a visually diverse system from being called successful when it is too labour-intensive or dependent on purchased biomass.



## Seven rules for productive natural farming

The most suitable system will differ by agro-ecology, irrigation, soil depth, livestock availability and market. However, the following design rules are widely useful.

**1. Retain one priority cereal but break the cereal-cereal chain.** Where household food security or assured procurement makes rice or wheat essential, retain it. Add mungbean, lentil, chickpea, cowpea or a green-manure legume in the next window instead of converting the entire farm to unfamiliar crops.

**2. Place a pulse in space or time.** Use an intercrop where rainfall is uncertain and a rotation where mechanised harvesting or separate management is important. Select compatible duration and canopy so that the pulse does not become a competitor.

**3. Grow the mulch before demanding the mulch.** Natural farming needs biomass. Reserve crop residues, grow fodder or cover crops, use border biomass and integrate livestock. Do not recommend heavy mulching where the farm has no reliable biomass source.

**4. Treat weeds as a first-month emergency.** Weeds consume moisture and nutrients when biological nutrient release is still slow. Use stale seedbeds, line sowing, optimum plant population, residue cover, wheel hoes and timely hand or mechanical weeding.

**5. Feed the pulse correctly.** Use healthy seed, recommended *Rhizobium* culture where appropriate, and correct deficiencies of phosphorus, sulphur and micronutrients through locally permitted sources and soil-test guidance. Poor nodulation should be diagnosed, not romanticised.

**6. Judge the whole system, not one crop.** Compare cereal-equivalent or crop-equivalent yield, annual net return, cost of cultivation, labour demand, soil cover days and yield stability. A slightly lower cereal yield

may still give higher annual profit when the pulse harvest and lower input cost are included.

**7. Convert gradually and keep a comparison strip.** Begin with 10-25% of the farm, use a locally proven crop combination and maintain a conventional or integrated comparison strip. Expand only after two or three seasons of records.

### A safe, stepwise transition

A safe transition begins before sowing. Map the farm's residue production, cattle resources, irrigation, labour and market. Identify the most exhaustive crop and the longest bare-soil period. The first intervention should usually be a pulse or cover crop in that gap, not the sudden removal of every external nutrient source.

During the first year, choose a low-risk block. Keep the main cereal on only the area that can be supported with residue and timely weed control. Introduce a short-duration pulse after harvest or as a row intercrop. Retain at least part of the residue, use seed treatment and locally validated natural preparations, and correct severe soil constraints. In fields with very low organic matter or a long history of residue removal, a phased transition with farmyard manure or other permitted organic inputs may protect income (Kumar et al. 2020).

During the second and third years, increase crop diversity rather than merely increasing the dose of liquid formulations. Add a pulse, oilseed, fodder or vegetable that uses a different rooting zone and marketing window. Integrate trees or perennial border plants where appropriate. Review the records after every season. A crop combination that gives attractive gross output but demands excessive labour, irrigation or purchased biomass is not truly low-cost.

### Measure the system, not only the main crop

Farmers and extension workers should record five indicators: (i) yield of every component crop,



converted to a common equivalent yield only for comparison; (ii) total paid-out cost and family labour; (iii) net return from the full year, including fodder and by-products; (iv) days of soil cover and quantity of residue returned; and (v) simple soil indicators such as organic carbon, infiltration, bulk density, pH and available nutrients. Nodulation, weed density and pest incidence should also be observed. These records reveal whether the system is improving or merely surviving on stored soil fertility.

### Where natural farming should not be forced

Natural farming should not be promoted as one fixed practice for every field. Highly nutrient-depleted soils, farms without biomass or livestock access, severe salinity or acidity, poorly drained heavy soils, and high-yield cereal monocultures may require site-specific correction and a longer transition (Kumar et al. 2020; Smith et al. 2020). Pulses also fail in waterlogged soil, under unsuitable pH or when seed and Rhizobium compatibility is poor. Farmers should use recommendations from the nearest State Agricultural University, ICAR institute or Krishi Vigyan Kendra and test the system locally.

### Summary

Natural farming becomes productive when the cropping system, not only the input, is redesigned. Pulse-based rotations, intercrops and rice-fallow pulses often provide a better starting point than cereal-cereal monocultures because they reduce dependence on external nitrogen, diversify roots and residues, keep the soil covered and add another source of food and income. Cereals can remain important, but they should be supported by legumes, mulch, biomass recycling, timely weed control and gradual transition. Success must be judged from annual system yield, net return, labour, yield stability and soil health rather than from the yield of one crop in one season. The practical strategy is to start small, retain a comparison strip, record results for two or

three seasons and expand only the cropping systems that match the farm's ecology and resources.

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# Peri-Urban Gardens: Greening the Space Between Cities and Villages

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Peri-urban gardens have emerged as an important component of sustainable urban development by bridging the gap between expanding cities and rural landscapes. These gardens, established in the transitional zones surrounding urban areas, produce fresh vegetables, fruits, flowers, herbs, and other high-value crops while providing multiple ecological, economic, and social benefits. Their proximity to urban markets ensures reduced transportation costs, lower post-harvest losses, and improved availability of nutritious food. Beyond food production, peri-urban gardens contribute to environmental sustainability by increasing green cover, conserving biodiversity, recycling organic waste, reducing urban heat island effects, and promoting efficient water management. They also create employment opportunities for farmers, women, self-help groups (SHGs), and young entrepreneurs through activities such as nursery raising, protected cultivation, composting, value addition, and direct marketing. The integration of modern technologies, including protected cultivation, hydroponics, artificial intelligence (AI), IoT, GIS, and digital marketing platforms, has further enhanced productivity, resource-use efficiency, and market access. However, challenges such as rapid urbanization, land conversion, water scarcity, pollution, climate change, and inadequate policy support threaten the sustainability of peri-urban agriculture. Strengthening institutional support, promoting climate-smart technologies, and integrating peri-urban gardens into urban planning are essential for developing resilient food systems, improving livelihoods, and creating healthier, greener, and more sustainable cities.

## Introduction

The world is urbanizing at an unprecedented pace. According to the Food and Agriculture Organization (FAO), more than half of the world's population now lives in urban areas, and this proportion is expected to increase further in the coming decades. Rapid urban expansion has increased the demand for food, water, housing, and infrastructure while simultaneously reducing agricultural land surrounding cities. As cities continue to spread into rural landscapes, a unique transition zone known as the peri-urban area has emerged. These regions represent the interface between urban and rural environments, where agriculture, industry, housing, and natural ecosystems coexist and compete for land and resources. Properly managed peri-urban areas can play a critical role in ensuring food security, environmental sustainability, and resilient urban development.

Peri-urban agriculture has gained global recognition as an effective strategy for supplying fresh food to expanding urban populations while creating employment opportunities and improving environmental quality. Unlike conventional rural agriculture, peri-urban farming is closely connected to urban consumers and markets, allowing producers to supply fresh vegetables, fruits, flowers, herbs, milk, eggs, and other agricultural commodities with minimal transportation and post-harvest losses. The FAO recognizes urban and peri-urban agriculture as an important component of sustainable food systems because it contributes simultaneously to better production, better nutrition, a better environment, and a better life.

Among various forms of peri-urban agriculture, peri-urban gardens have become increasingly important because they utilize limited land efficiently while providing multiple ecological, economic, and social





benefits. These gardens include household kitchen gardens, community gardens, institutional gardens, rooftop gardens, commercial vegetable farms, orchards, floriculture units, medicinal plant gardens, and protected cultivation systems. They not only produce fresh food but also improve urban biodiversity, recycle organic waste, reduce the urban heat island effect, and create healthier living environments.

### What is Peri-Urban Gardens?

Peri-urban gardens are cultivation spaces located on the outskirts of cities where agricultural activities are practiced under the influence of both urban and rural environments. They integrate crop production, horticulture, floriculture, livestock, aquaculture, composting, and value addition to meet the growing food demands of nearby cities. According to FAO, urban and peri-urban agriculture includes not only food production but also processing, marketing, recycling, and distribution systems that make cities more resilient and sustainable.

Unlike conventional farming, peri-urban gardens are highly market-oriented. Farmers cultivate high-value, perishable crops such as leafy vegetables, tomatoes, cucumbers, capsicum, strawberries, mushrooms, flowers, herbs, and medicinal plants because these products command better prices in nearby urban markets. Since transportation distances are short, produce reaches consumers quickly, preserving freshness, nutritional quality, and market value.



Source: [https://stockcake.com/i/urban-garden-oasis\\_440584\\_176729](https://stockcake.com/i/urban-garden-oasis_440584_176729)

### Global and Indian Scenario

Urban and peri-urban agriculture is practiced in almost every region of the world. FAO estimates that nearly 800 million people are involved in urban and peri-urban agriculture, while approximately 266 million urban households in developing countries participate in crop production. These farming systems contribute significantly to local food availability, employment generation, waste recycling, and climate resilience. Countries such as the Netherlands, France, Brazil, Kenya, Ethiopia, China, Cuba, Nepal, and India have successfully integrated peri-urban agriculture into local food systems using innovative production technologies and supportive policies.

In India, rapid urbanization has created growing opportunities for peri-urban horticulture around metropolitan cities such as Delhi, Bengaluru, Hyderabad, Pune, Chennai, Kolkata, and Mumbai. In Delhi peri-urban agriculture provides employment, income, and nutritious food for landless labourers and smallholder farmers while supplying vegetables and milk to the city, vegetable gardening, mixed farming, nursery production, mushroom cultivation, and protected cultivation are among the most common peri-urban agricultural enterprises in India.

### Types of Peri-Urban Gardens

Peri-urban gardens exist in diverse forms depending on land availability, market demand, and production objectives. Household kitchen gardens primarily supply vegetables and fruits for family consumption, whereas community gardens promote collective food production and social interaction. Commercial vegetable farms cultivate high-value crops for urban markets, while rooftop gardens and terrace farming efficiently utilize unused urban spaces. Institutional gardens established in schools, universities, hospitals, and offices provide educational, nutritional, and recreational benefits. Protected cultivation systems such as polyhouses, shade-net





houses, hydroponics, and vertical farming enable year-round production with higher resource-use efficiency.

### **Importance for Food and Nutritional Security**

One of the greatest contributions of peri-urban gardens is their role in improving food and nutritional security. Fresh vegetables and fruits produced near cities reach consumers within a few hours of harvest, minimizing post-harvest losses and preserving nutritional quality. Local production also reduces transportation costs, lowers greenhouse gas emissions associated with long-distance food transport, and strengthens urban food supply chains during emergencies or natural disasters. Studies from India and several developing countries show that peri-urban agriculture provides both income and nutritious food for vulnerable households while increasing the availability of affordable vegetables in urban markets.

For farming families, peri-urban gardens diversify income sources and improve dietary diversity through the regular consumption of fresh vegetables, fruits, herbs, and animal products. Women's participation in kitchen gardens and community gardens has been particularly important in improving household nutrition, empowering self-help groups, and promoting local entrepreneurship. Consequently, peri-urban gardens have become an integral component of sustainable urban food systems that support both livelihoods and public health.

### **Environmental Benefits of Peri-Urban Gardens**

Peri-urban gardens contribute significantly to environmental sustainability by acting as "green lungs" around expanding cities. They increase green cover, improve air quality, reduce dust and noise pollution, and help mitigate the urban heat island effect by lowering surrounding temperatures. Trees, shrubs, vegetables, and flowering plants absorb carbon dioxide while releasing oxygen, thereby

improving the urban microclimate and contributing to climate change mitigation. These green spaces also serve as habitats for birds, pollinators, butterflies, earthworms, and beneficial insects, thereby conserving biodiversity in rapidly urbanizing landscapes. FAO recognizes urban and peri-urban agriculture as an important strategy for creating more resilient, sustainable, and environmentally friendly cities.

Peri-urban gardens also promote the efficient recycling of natural resources. Organic household waste, vegetable residues, and market waste can be converted into compost or vermicompost, reducing the burden on municipal waste disposal systems while improving soil fertility. In several cities, treated wastewater is safely reused for irrigation under appropriate management practices, helping conserve freshwater resources. Sustainable practices such as rainwater harvesting, mulching, conservation tillage, and drip irrigation further improve water-use efficiency and reduce environmental degradation. Proper integration of agriculture into urban planning can also improve soil and water conservation, enhance biodiversity, and increase the recreational and aesthetic value of green spaces.

Another important contribution of peri-urban gardens is strengthening urban resilience. During disruptions in food supply chains caused by pandemics, floods, droughts, or other emergencies, locally produced food helps maintain access to fresh vegetables and fruits. Short supply chains also reduce transportation requirements, fuel consumption, and post-harvest losses, making local food systems more sustainable.

### **Economic and Livelihood Opportunities**

Peri-urban gardening has emerged as a profitable enterprise because of its proximity to urban consumers. Farmers can cultivate high-value crops such as leafy vegetables, tomatoes, capsicum, cucumber, strawberry, mushrooms, flowers,



medicinal plants, and herbs, which command premium prices in nearby markets. Since produce reaches consumers within a short period after harvest, farmers receive better returns while consumers obtain fresher and more nutritious food. This close producer-consumer linkage reduces dependence on intermediaries and increases farmers' share of the consumer price.

The sector also generates employment opportunities for rural youth, women, self-help groups (SHGs), Farmer Producer Organizations (FPOs), and urban entrepreneurs. Activities such as nursery production, floriculture, seedling raising, mushroom cultivation, compost production, protected cultivation, landscaping, and value addition create year-round employment. Women play a particularly important role in managing kitchen gardens, community gardens, processing, and direct marketing, thereby improving household income and nutritional security.

In many countries, peri-urban agriculture has become an important component of local economic development. Successful examples from Latin America, Africa, and Asia demonstrate that integrating agriculture into city planning can improve livelihoods while enhancing climate resilience and food security.

### **Social and Health Benefits**

Beyond food production, peri-urban gardens provide valuable social and health benefits. Community gardens strengthen neighbourhood relationships, encourage collective action, and create opportunities for people of different age groups to participate in gardening activities. Gardening has been shown to reduce stress, improve mental well-being, encourage physical activity, and promote healthier lifestyles through increased consumption of fresh fruits and vegetables. These gardens also serve as educational spaces where school children, students, and urban

residents learn about food production, biodiversity, composting, and environmental conservation.

Peri-urban gardens contribute to public health by increasing the availability of safe, fresh, and nutritious food. Shorter supply chains reduce storage time and post-harvest deterioration, helping preserve vitamins and minerals in vegetables and fruits. Household kitchen gardens also improve dietary diversity and nutrition, particularly among women and children. During periods of food price inflation or supply disruptions, locally grown produce provides an affordable source of nutritious food for urban households.

### **Modern Technologies Transforming Peri-Urban Gardening**

Rapid technological advancements are transforming peri-urban gardening into a highly efficient and climate-resilient production system. Protected cultivation technologies such as polyhouses, shade-net houses, and low tunnels enable year-round production while protecting crops from adverse weather conditions. Hydroponics, aeroponics, aquaponics, and vertical farming allow vegetables and herbs to be cultivated with significantly less land and water than conventional farming, making them particularly suitable for urban and peri-urban environments.

Digital agriculture is further enhancing productivity through the integration of Artificial Intelligence (AI), Geographic Information Systems (GIS), drones, remote sensing, Internet of Things (IoT) sensors, and mobile-based advisory services. Soil moisture sensors and automated irrigation systems optimize water use, while drones monitor crop health and detect nutrient deficiencies or pest outbreaks. AI-powered decision-support systems analyse weather forecasts, crop growth, and satellite imagery to recommend appropriate irrigation schedules, fertilizer application, and pest management practices. These technologies improve



resource-use efficiency, reduce production costs, and increase profitability while supporting climate-smart agriculture.

The adoption of e-commerce platforms and digital marketing has further expanded market opportunities for peri-urban producers. Farmers can now connect directly with consumers, supermarkets, restaurants, and online grocery platforms, reducing marketing costs and increasing farm income. As cities continue to grow, integrating modern technologies with sustainable production practices will play a crucial role in ensuring the long-term success of peri-urban gardens and strengthening urban food systems.

### Challenges and Constraints

Despite their numerous benefits, peri-urban gardens face several challenges that limit their expansion and long-term sustainability. Rapid urbanization is the most significant threat, as fertile agricultural land is continuously converted into residential colonies, industrial estates, commercial complexes, and transportation infrastructure. As cities expand, land prices increase substantially, making farming economically less attractive and encouraging farmers to sell their land for non-agricultural purposes. Consequently, the area available for food production around cities continues to decline (FAO, 2022).

Water scarcity is another major constraint. Peri-urban farmers often compete with urban households and industries for limited freshwater resources. In many locations, groundwater depletion, irregular rainfall, and climate change have reduced irrigation water availability. Although treated wastewater can supplement irrigation, improper use of untreated wastewater may introduce heavy metals, pathogens, and chemical contaminants into agricultural soils and crops, posing risks to food safety and public health (Hamilton et al., 2007).

Pollution also affects peri-urban agriculture. Industrial emissions, vehicular pollution, plastic

waste, and indiscriminate disposal of municipal solid waste can contaminate soils, water bodies, and crops. Farmers often face inadequate access to quality planting material, organic inputs, credit, crop insurance, and extension services. Labour shortages, increasing input costs, and market price fluctuations further reduce profitability, especially for small and marginal farmers (Zezza & Tasciotti, 2010).

Climate change has added another layer of uncertainty. Rising temperatures, erratic rainfall, droughts, floods, and pest outbreaks affect crop productivity and increase production risks. Addressing these challenges requires integrated urban planning, sustainable natural resource management, effective policies, and stronger institutional support.

### Conclusion

Peri-urban gardens represent far more than small cultivation spaces surrounding cities—they are essential components of sustainable urban development. By producing fresh and nutritious food close to consumers, they strengthen food and nutritional security, generate employment, improve household incomes, conserve natural resources, enhance biodiversity, and contribute to climate change mitigation. These gardens also improve urban environmental quality by increasing green cover, recycling organic waste, reducing transportation-related emissions, and promoting healthier lifestyles.

However, rapid urbanization, land conversion, water scarcity, pollution, and climate change threaten the sustainability of peri-urban agriculture. Addressing these challenges requires integrated policies, scientific research, efficient natural resource management, and strong institutional support. Agricultural extension services, supported by digital technologies and Artificial Intelligence, will continue to play a vital role in disseminating climate-smart technologies and empowering farmers.



As cities continue to expand, integrating peri-urban gardens into urban planning and agricultural development strategies will become increasingly important. Investment in sustainable production systems, innovative technologies, community participation, and supportive government policies can transform peri-urban gardens into vibrant green spaces that nourish people, protect the environment, and strengthen resilient food systems for future generations.

**"Peri-urban gardens are where agriculture meets urban life-cultivating not only fresh food but also healthier communities, greener cities, and a more sustainable future."**

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# Role of Agricultural Extension in Promoting Carbon Farming: Cultivating the Future While Protecting the

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Carbon farming has emerged as a sustainable approach to mitigating climate change by enhancing carbon sequestration while improving soil health, farm productivity, and environmental sustainability. However, its successful adoption largely depends on effective agricultural extension services. Agricultural extension plays a vital role in creating awareness, building farmers' capacities, disseminating climate-smart technologies, providing advisory services, and facilitating access to carbon markets. Through training, demonstrations, digital advisory platforms, and farmer organizations, extension professionals bridge the gap between research and farming communities, encouraging the adoption of sustainable agricultural practices. This article highlights the role of agricultural extension in promoting carbon farming, the challenges affecting its adoption, and strategies to strengthen extension systems for advancing climate-resilient and low carbon agriculture.

## Introduction

Agriculture has always been the backbone of India's economy, feeding millions while supporting rural livelihoods. However, the sector is increasingly facing the impacts of climate change in the form of erratic rainfall, rising temperatures, declining soil fertility, and frequent extreme weather events. Amid these challenges, carbon farming has emerged as a promising approach that enables farmers to improve soil health, enhance productivity, and contribute to climate change mitigation (Lal, 2023; IPCC, 2023). Yet, the success of carbon farming depends largely on one critical factor effective agricultural extension (FAO, 2023).

## What is Carbon Farming?

Carbon farming refers to a range of agricultural practices that capture and store carbon from the atmosphere in soils and vegetation while reducing greenhouse gas emissions (Lal, 2020). It transforms agricultural fields into natural carbon sinks, making farming both productive and environmentally sustainable (IPCC, 2023).

Some of the widely adopted carbon farming practices include:

- Conservation tillage and zero tillage
- Cover cropping
- Crop residue retention
- Agroforestry
- Integrated nutrient management
- Organic farming
- Precision agriculture
- Efficient irrigation and water conservation
- Integrated crop-livestock systems

These practices not only reduce agriculture's carbon footprint but also improve soil fertility, conserve moisture, and increase resilience to climate change (FAO, 2023).

## Role of Agricultural Extension

While carbon farming offers immense benefits, many farmers remain unaware of its techniques, advantages, and economic opportunities. This is where agricultural extension acts as the bridge





between scientific innovation and field-level adoption (Anderson & Feder, 2007).

### **Creating Awareness**

Extension professionals educate farmers about climate change, sustainable agriculture, and carbon sequestration through awareness campaigns, village meetings, exhibitions, and field demonstrations. They help farmers understand that protecting the environment can also improve farm profitability (FAO, 2023).

### **Building Skills**

Knowledge alone is not enough. Farmers need practical skills to adopt new practices successfully. Extension agencies organize training programmes, Farmer Field Schools, and on-farm demonstrations that enable farmers to learn by doing. Seeing successful demonstrations often builds confidence and encourages wider adoption (Davis et al., 2012).

### **Bringing Science to the Farm**

Research institutions continuously develop improved technologies for climate-smart agriculture. Extension personnel ensure these innovations reach farmers in simple and practical forms. Whether it is introducing biofertilizers, precision nutrient management, or agroforestry models, extension services make scientific knowledge accessible to farming communities (ICAR, 2023).

### **Providing Timely Advisory Services**

Modern extension has moved beyond face-to-face communication. Mobile phones, WhatsApp groups, mobile applications, digital advisory platforms, and weather-based agro-advisories now provide farmers with timely recommendations on crop management, irrigation scheduling, nutrient application, and residue management all of which contribute to carbon farming (World Bank, 2024).

### **Encouraging Collective Action**

Small and marginal farmers often face difficulties in adopting new technologies individually. Extension professionals encourage the formation of Farmer Producer Organizations (FPOs), self-help groups, and farmer clubs that promote collective learning, resource sharing, and better access to markets and financial support (FAO, 2023).

### **Connecting Farmers to Carbon Markets**

One of the most exciting opportunities in carbon farming is the potential to earn income through carbon credits. Extension agencies can educate farmers about carbon markets, certification procedures, record keeping, and aggregation models, enabling them to participate in emerging green economy initiatives (World Bank, 2024).

### **Monitoring Progress**

Extension personnel also play an important role in documenting field experiences, monitoring adoption, collecting feedback, and assessing the environmental and economic impacts of carbon farming practices. Their observations help researchers improve technologies and assist policymakers in designing effective climate-related programmes (FAO, 2021).

### **Limitations**

Despite its enormous potential, carbon farming faces several hurdles:

- Limited awareness among farmers
- Lack of technical expertise
- Small and fragmented landholdings
- Inadequate financial incentives
- Difficulty in measuring soil carbon
- Limited access to carbon credit markets
- Weak institutional coordination



Addressing these challenges requires strong collaboration among research institutions, extension agencies, policymakers, private organizations, and farming communities (IPCC, 2023).

### Way Forward

Agricultural extension must evolve from simply transferring technologies to becoming a facilitator of climate resilience. Continuous capacity building of extension professionals, greater use of digital technologies, establishment of climate-smart villages, promotion of participatory learning, and stronger policy support can significantly accelerate the adoption of carbon farming across India (FAO, 2023; World Bank, 2024). Carbon farming is not merely a climate solution it is an investment in healthier soils, resilient farms, and sustainable livelihoods. By empowering farmers with knowledge, skills, and opportunities, agricultural extension can lead the transformation toward a greener and more prosperous agricultural future (Lal, 2023).

### Conclusion

The future of agriculture lies in producing more while protecting natural resources. Carbon farming offers farmers a unique opportunity to improve productivity, restore soil health, and contribute to combating climate change. Agricultural extension stands at the heart of this transformation, ensuring that scientific innovations reach every field and every farmer. With effective extension support, Indian farmers can become not only food producers but also guardians of the environment, helping build a climate-resilient and sustainable future for generations to come (FAO, 2023; IPCC, 2023).

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# Biochar in Sustainable Agriculture

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Biochar has emerged as a promising soil amendment and climate-smart agricultural input due to its multifunctional role in improving soil fertility, enhancing crop productivity, mitigating greenhouse gas emissions, and supporting long-term carbon sequestration. Produced through the thermochemical conversion of biomass under oxygen-limited conditions, biochar possesses unique physical and chemical characteristics such as high porosity, large surface area, and strong adsorption capacity. These properties contribute significantly to improved nutrient retention, water holding capacity, microbial activity, and soil aggregation. The growing concerns regarding soil degradation, declining soil organic matter, climate change, and unsustainable dependence on chemical fertilizers have intensified global interest in biochar-based agricultural systems. This article synthesizes current knowledge on biochar production technologies, feedstock sources and physicochemical properties. It further examines the effects of biochar on soil physical, chemical, and biological properties, crop productivity, nutrient cycling, water retention, and greenhouse gas mitigation. The article also discusses biochar applications in sustainable agriculture, environmental remediation, and climate change mitigation. The article concludes by identifying future research priorities focused on optimizing biochar production, improving crop-specific applications, integrating biochar into regenerative agriculture systems, and developing supportive policy frameworks. Overall, biochar represents a sustainable and resilient strategy for enhancing agricultural productivity while simultaneously addressing global environmental challenges.

## 1.Introduction

Agriculture is facing unprecedented challenges due to increasing population pressure, declining soil fertility, climate change, water scarcity, and environmental degradation (Gomiero,2016). Global food demand is expected to rise substantially in the coming decades, placing immense pressure on agricultural systems to produce more food with limited natural resources. Conventional agricultural practices characterized by intensive tillage, excessive fertilizer application, residue burning, and monocropping have accelerated soil degradation and reduced soil organic matter content (Sarkar et al., 2025a). Such practices negatively affect soil

structure, nutrient availability, microbial diversity, and long-term productivity. Climate change further intensifies these challenges through increasing temperatures, erratic rainfall patterns, prolonged droughts, and increased frequency of extreme weather events. Agriculture itself contributes significantly to greenhouse gas emissions, particularly carbon dioxide (CO<sub>2</sub>), methane (CH<sub>4</sub>), and nitrous oxide (N<sub>2</sub>O). Therefore, sustainable agricultural practices that simultaneously improve productivity and reduce environmental impacts are urgently required (Sarkar et al., 2023). Biochar has gained considerable attention as a sustainable soil amendment capable of improving soil health, enhancing crop productivity, and mitigating climate



change (Ayaz et al., 2021). Biochar is a stable, carbon-rich material produced by heating organic biomass under oxygen-limited conditions through processes such as pyrolysis, gasification, or hydrothermal carbonization. The agricultural importance of biochar lies in its ability to improve soil physical, chemical, and biological properties. Biochar application can increase soil porosity, water holding capacity, aggregate stability, nutrient retention, and cation exchange capacity. It can also reduce soil acidity, improve microbial activity, and enhance nutrient cycling. Furthermore, biochar serves as a long-term carbon sink due to its highly stable aromatic carbon structure, thereby contributing to carbon sequestration and climate change mitigation. This article aims to provide a comprehensive overview of biochar, focusing on feedstocks and production technologies, physicochemical characteristics, effects on soil physical, chemical, and biological properties, impacts on crop productivity and nutrient cycling, role in climate change mitigation and carbon sequestration, and environmental remediation applications. Overall, the article seeks to evaluate the potential of biochar as a sustainable tool for improving soil health, enhancing agricultural productivity, and supporting global environmental sustainability.

## 2. Feedstocks Used for Biochar Production

Biochar can be produced from diverse feedstocks, including woody and forestry residues, agricultural wastes, animal manures, municipal and industrial organic wastes, and aquatic biomass. Feedstock type strongly influences biochar yield and physicochemical properties, including elemental

composition, pH, surface functionality, pore structure, and morphology. These properties are also substantially influenced by pyrolysis conditions, particularly temperature and other process parameters (Gholizadeh et al., 2024). Table 1 presents the nutrient composition of various biochars produced from different feedstocks at different pyrolysis temperatures, highlighting the influence of feedstock characteristics and thermal processing conditions on the nutrient content of the resulting biochar. Woody and forestry residues generally produce carbon-rich, aromatic, and relatively stable biochars with good sorption properties, making them suitable for carbon sequestration and environmental remediation. Agricultural residues such as rice husk, cereal straw, maize stover, sugarcane bagasse, and nutshells are abundant and low-cost feedstocks; their biochars vary widely in mineral composition (Jalali et al., 2025). Manure-derived biochars generally contain higher ash, mineral, and nutrient concentrations and greater alkalinity than woody biochars, supporting their use for nutrient management and acidic soil amelioration (Hassan et al., 2020). Municipal and industrial wastes provide opportunities for waste valorization and nutrient recovery but may contain contaminants, necessitating strict feedstock characterization and quality control. Aquatic biomass, including algae, seaweed, and invasive aquatic plants, is an emerging feedstock that may produce nutrient-rich biochars but can present concerns related to salinity and accumulated contaminants. Overall, feedstock selection should be matched to the intended application and combined with optimized pyrolysis conditions to achieve the desired balance among carbon persistence, nutrient supply, soil improvement, and environmental safety.

**Table 1.** Nutrient composition of various biochars at different pyrolysis temperatures (Ayaz et al., 2021)

| Biochar Feedstock | Pyrolysis Temp. (°C) | pH   | C (%) | N(%) | C/N | P(%)  | K(%)  |
|-------------------|----------------------|------|-------|------|-----|-------|-------|
| Corn stover       | 600                  | 9.95 | 69.8  | 1.01 | 70  | 0.181 | 2.461 |



|                |     |      |      |      |    |         |        |
|----------------|-----|------|------|------|----|---------|--------|
| Corn stover    | 300 | 7.33 | 59.5 | 1.16 | 51 | 0.137   | 1.705  |
| Pearl millet   | 400 | 10.6 | 64   | 1.10 | 58 | 1.60    | 2.52   |
| Peanut hull    | 400 | 10.0 | 65.5 | 2.0  | 33 | 0.00162 | 0.0015 |
| Dairy manure   | 700 | 9.9  | 56.7 | 1.51 | 38 | 1.69    | 2.31   |
| Cow manure     | 500 | 9.20 | 33.6 | 0.15 | 22 | 0.814   | 0.005  |
| Poultry litter | 350 | 8.7  | 51.1 | 4.45 | 12 | 2.08    | 4.58   |
| Turkey litter  | 700 | 9.9  | 44.8 | 1.94 | 23 | 3.63    | 5.59   |

### 3. Biochar Production Technologies

Biochar and related carbonaceous materials can be produced through several thermochemical conversion technologies (Fig.1), with feedstock characteristics and operating conditions strongly influencing product yield and properties. The principal technologies include pyrolysis, gasification, hydrothermal carbonization (HTC), torrefaction, and emerging approaches such as microwave-assisted pyrolysis. However, these processes produce different solid products: pyrolysis primarily produces biochar, gasification generates gasification-derived char as a by-product, HTC produces hydrochar, and torrefaction produces a carbon-enriched solid primarily intended for fuel upgrading. The selection of technology depends on feedstock properties, moisture content, desired product characteristics, energy requirements, and end-use applications.

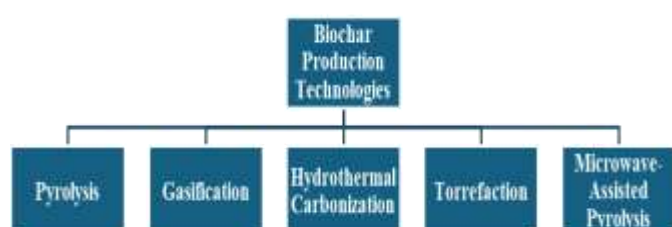


Fig.1: Biochar production technologies

#### 3.1 Pyrolysis

Pyrolysis is the most established route for biochar production, involving the thermal decomposition of biomass under oxygen-limited conditions, generally within approximately 300–600°C, to produce biochar, bio-oil, and non-condensable gases. Product yields and biochar properties depend on feedstock composition, temperature, heating rate, residence time, and reactor configuration. Slow pyrolysis uses relatively low heating rates and longer residence times and generally favours higher biochar yields, whereas fast pyrolysis employs rapid heating and short vapour residence times and is primarily optimized for bio-oil production. Intermediate pyrolysis operates between these regimes and can facilitate more balanced production of biochar, bio-oil, and gases. Increasing pyrolysis temperature generally decreases biochar yield while increasing carbonization and aromaticity, although the resulting properties depend strongly on feedstock and process conditions (Gholizadeh et al., 2024; Jalali et al., 2025).

#### 3.2 Gasification

Gasification is a high-temperature thermochemical process in which biomass is partially oxidized using limited air, oxygen, or steam, generally at temperatures above 700°C. The primary product is syngas, mainly comprising CO, H<sub>2</sub>, CH<sub>4</sub>, and CO<sub>2</sub>,





while a smaller fraction of carbonaceous solid residue, termed gasification-derived char, is also produced. Compared with pyrolysis, gasification generally yields less solid char because a larger proportion of biomass carbon is converted into gaseous products. Gasification-derived char often contains relatively high ash and mineral contents and may exhibit considerable alkalinity, making it potentially useful for soil amendment and remediation. However, its properties are strongly dependent on feedstock and gasification conditions and should therefore be evaluated for specific applications.

### 3.3 Hydrothermal Carbonization

Hydrothermal carbonization (HTC) converts wet biomass into a carbon-rich solid known as hydrochar under hot, pressurized water, typically at approximately 180-250°C (Sivaranjane et al., 2023). Unlike dry thermochemical processes, HTC requires little or no energy-intensive drying, making it particularly suitable for high-moisture feedstocks such as sewage sludge, manure, food waste, and aquatic biomass. Hydrochar is formed through hydrolysis, dehydration, decarboxylation, condensation, and polymerization reactions and generally differs from pyrolysis biochar in its chemical structure and surface properties. It typically retains more oxygen-containing functional groups and exhibits lower aromaticity and carbon stability than biochar produced at higher pyrolysis temperatures, although its properties vary with feedstock and process conditions.

### 3.4 Torrefaction

Torrefaction is a mild thermal treatment conducted at approximately 200-300°C under oxygen-limited or inert conditions (Yaashikaa et al., 2020). It primarily removes moisture and volatile compounds, producing a carbon-enriched solid with improved energy density, grindability, hydrophobicity, and storage stability. Torrefied biomass may have

potential for soil and environmental applications, torrefaction is primarily used for biomass fuel upgrading rather than conventional biochar production.

### 3.5 Microwave-Assisted Pyrolysis

Microwave-assisted pyrolysis (MAP) is an emerging technology that uses electromagnetic energy to heat biomass rapidly and volumetrically, potentially reducing heating time and improving process efficiency compared with conventional external heating. MAP can influence biochar yield and surface characteristics and may facilitate the production of materials with enhanced porosity and adsorption performance under suitable operating conditions. However, microwave heating efficiency depends on feedstock dielectric properties, moisture content, reactor configuration, and microwave power, and challenges related to scale-up, energy consumption, equipment cost, and process control remain.

### 4. Biochar Effects on Soil Properties

Biochar significantly influences soil physical, chemical, and biological properties (Fig. 2) due to its porous structure, high surface area, stability, and reactive functional groups. Its effectiveness depends on feedstock type, pyrolysis temperature, application rate, soil characteristics, climatic conditions, and duration of application. Numerous studies have reported improvements in soil fertility, nutrient availability, microbial activity, and overall soil health following biochar incorporation.

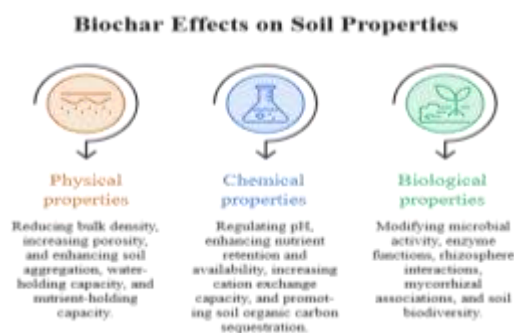


Fig.2 Biochar Effects on Soil Properties



#### 4.1 Effects on Soil Physical Properties

Biochar improves soil physical properties by reducing bulk density, increasing porosity, and enhancing soil aggregation, water-holding capacity (WHC), and nutrient-holding capacity (NHC). Its porous structure promotes water and nutrient retention, improves infiltration, aeration, and root growth, and enhances water- and nutrient-use efficiency, particularly in sandy and coarse-textured soils. Biochar application can reduce soil bulk density by 3-31% and increase porosity by 14-64% (Radwan et al., 2020), while improved aggregation and structural stability may also reduce runoff and soil erosion. The magnitude of these effects depends on biochar characteristics, soil texture, application rate, and pyrolysis conditions.

#### 4.2 Effects on Soil Chemical Properties

Biochar substantially improves soil chemical properties by regulating pH, enhancing nutrient retention and availability, increasing cation exchange capacity (CEC), and promoting soil organic carbon (SOC) sequestration (Sun, et al., 2022). Its alkaline nature, resulting from ash and basic cations such as Ca, Mg, and K, can neutralize acidic soils, reduce aluminum toxicity, and improve nutrient availability. Biochar also retains nutrients through adsorption, ion exchange, and surface complexation, thereby reducing the leaching of N, P, and other essential nutrients and improving fertilizer-use efficiency. Its negatively charged surfaces can increase soil CEC, while the development of oxygen-containing functional groups during aging may further enhance nutrient retention. The stable aromatic carbon structure of biochar is resistant to microbial decomposition, contributing to long-term SOC accumulation and carbon sequestration. In addition, biochar can immobilize potentially toxic heavy metals such as Cd, Pb, Cu, and Zn through adsorption, precipitation, and ion exchange, thereby reducing their bioavailability and toxicity. Overall, these chemical effects contribute to improved soil

fertility, nutrient conservation, carbon storage, and environmental quality, although their magnitude depends on biochar characteristics, application rate, soil properties, and environmental conditions.

#### 4.3 Effects on Soil Biological Properties

Biochar positively influences soil biological properties by modifying microbial activity, enzyme functions, rhizosphere interactions, mycorrhizal associations, and soil biodiversity (Lehmann et al., 2021). Its porous structure provides favourable habitats for microorganisms and protects them from environmental stress, thereby enhancing microbial biomass, respiration, and enzymatic activities involved in carbon, nitrogen, and phosphorus cycling. Biochar can stimulate enzymes such as urease, phosphatase, dehydrogenase, and  $\beta$ -glucosidase, promoting nutrient transformation and availability. It also improves rhizosphere conditions by influencing root exudation, nutrient dynamics, and plant-microbe interactions, which can support root development and nutrient uptake. In addition, biochar may enhance arbuscular mycorrhizal colonization, improving phosphorus acquisition, drought tolerance, and plant resilience. By improving soil aeration, moisture retention, and carbon availability, biochar can also create favourable conditions for soil fauna such as earthworms and nematodes, thereby promoting soil biodiversity, ecosystem functioning, and overall soil resilience.

Overall, biochar improves soil physical structure, enhances nutrient retention, increases microbial activity, and contributes to long-term carbon sequestration. These combined effects enhance soil fertility, crop productivity, environmental sustainability, and resilience against climate-related stresses. However, the magnitude and direction of biochar effects vary considerably depending on feedstock source, pyrolysis conditions, soil type, crop species, environmental conditions, and management practices. Therefore, site-specific biochar application



strategies are essential for maximizing agricultural and environmental benefits.

### 5. Effect of Biochar on Soil Organic Matter

Biochar plays an important role in the stabilization and storage of soil organic matter (SOM) and soil organic carbon (SOC). Biochar can promote carbon accumulation within soil aggregates, particularly macroaggregates, thereby increasing the physical protection and stabilization of SOM (Wang et al., 2017). The formation of stable microaggregates can further enhance the long-term sequestration and stabilization of organic carbon. These effects may be influenced by biochar characteristics, particularly pyrolysis temperature, as low temperature biochars containing partially carbonized and relatively labile organic compounds may promote physical carbon fixation and interact differently with native SOM. However, biochar effects on native SOM dynamics are strongly dependent on soil texture and biochar properties. Biochar application may also induce short-term positive priming effects, stimulating the decomposition of native SOM in some soils. Therefore, the influence of biochar on SOM is complex and can involve both enhanced carbon stabilization and, under certain conditions, increased mineralization of native soil carbon, depending on soil texture, biochar characteristics, and environmental conditions (Ayaz et al., 2021).

### 6. Crop Productivity and Nutrient Cycling

Biochar can improve crop productivity and nutrient cycling by enhancing soil fertility, nutrient retention, water availability, and microbial activity (Lehmann et al., 2021). Its porous structure, high surface area, and adsorption capacity help retain nutrients and reduce their losses through leaching, runoff, and volatilization, thereby improving the use efficiency of nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), and magnesium (Mg). Biochar can also increase cation exchange capacity and gradually release retained nutrients, supporting sustained plant

uptake and potentially reducing fertilizer losses. Improvements in soil water-holding capacity, porosity, aggregation, and aeration further promote root development and nutrient acquisition, with benefits often being more pronounced in degraded, acidic, sandy, or nutrient-deficient soils. In addition, biochar may provide microsites for beneficial microorganisms, stimulating microbial activity and processes involved in carbon, nitrogen, and phosphorus cycling. These combined effects can enhance nutrient availability, plant growth, biomass production, and crop yield under favourable conditions. However, crop responses are highly variable and depend on biochar feedstock, pyrolysis conditions, application rate, soil properties, climate, and crop type. Excessive or inappropriate application may adversely affect nutrient balance or plant growth. Therefore, site-specific selection and optimized application rates are essential to maximize the agronomic benefits of biochar and support sustainable nutrient management.

### 7. Climate Change Mitigation and Carbon Sequestration

Climate change is primarily driven by the increasing atmospheric concentrations of anthropogenic greenhouse gases (GHGs), particularly carbon dioxide (CO<sub>2</sub>), methane (CH<sub>4</sub>), and nitrous oxide (N<sub>2</sub>O) (Sarkar et al., 2025b). Biochar has emerged as a promising climate-change mitigation strategy because it can facilitate long-term carbon sequestration while potentially reducing GHG emissions from agricultural soils. During photosynthesis, plants capture atmospheric CO<sub>2</sub> and convert it into biomass. When this biomass is converted into biochar through pyrolysis and subsequently incorporated into soil, a substantial fraction of the carbon is transformed into stable, aromatic structures that are resistant to microbial decomposition. This process can reduce the rate of carbon mineralization and enhance the long-term retention of biomass-derived carbon in soil, thereby contributing to atmospheric CO<sub>2</sub> removal and carbon



sequestration (Reddy, 2014). The stability of biochar carbon depends on feedstock characteristics, pyrolysis conditions, and soil environment, with highly carbonized biochars generally exhibiting greater persistence in soil. In addition to carbon sequestration, biochar may contribute to GHG mitigation by altering soil physical, chemical, and biological processes. Its porous structure can improve soil moisture retention, aeration, nutrient availability, and microbial habitat, which may influence carbon and nitrogen cycling. Biochar application has been reported to reduce emissions of CO<sub>2</sub>, CH<sub>4</sub>, and N<sub>2</sub>O in certain soil and cropping systems, although the magnitude and direction of these effects vary considerably with biochar properties, application rate, soil type, climate, and agricultural management practices. Biochar may reduce N<sub>2</sub>O emissions by modifying soil nitrogen transformations and improving nitrogen retention, while changes in soil redox conditions and microbial activity can influence CH<sub>4</sub> production and oxidation. These effects may be particularly relevant in flooded agricultural systems such as rice cultivation. The climate mitigation potential of biochar therefore extends beyond direct carbon storage and includes potential reductions in non-CO<sub>2</sub> GHG emissions. However, the overall climate benefit of biochar systems should be assessed through a life-cycle perspective that considers biomass production, feedstock collection and transport, pyrolysis energy requirements, biochar application, and long-term carbon persistence. Thus, biochar represents a potentially important component of climate-smart agriculture, offering opportunities to combine durable carbon sequestration with reductions in agricultural GHG emissions, although further long-term field studies are required to quantify its net climate-mitigation potential under diverse environmental and management conditions.

## 8. Constraints and Limitations

Despite its potential benefits, biochar adoption is constrained by considerable variability in

physicochemical properties arising from differences in feedstock and pyrolysis conditions, leading to inconsistent performance across soils and climates. High production, processing, and transportation costs further limit large-scale use, particularly among smallholder farmers. Long-term impacts on soil health, microbial communities, nutrient dynamics, and crop productivity remain insufficiently understood, while inappropriate application rates may alter soil pH or nutrient availability. Potential contaminants, including heavy metals and polycyclic aromatic hydrocarbons (PAHs), are additional concerns, especially for biochars derived from sewage sludge, industrial wastes, or contaminated biomass. The absence of harmonized quality standards and regulatory frameworks, combined with limited farmer awareness, technical capacity, and financial resources, also restricts wider adoption. Addressing these challenges requires long-term field research, standardized quality protocols, cost-effective production systems, supportive policies, and effective farmer training and extension services.

## 9. Future Research Directions

Future biochar research should prioritize feedstock- and application-specific production strategies that deliver predictable and targeted properties. Long-term, multi-location field trials are needed to assess biochar persistence and its effects on soil health, nutrient cycling, crop productivity, and greenhouse gas emissions under diverse agroecological conditions. Greater attention should also be given to biochar interactions with soil microorganisms, rhizosphere processes, and plant-microbe relationships. Research on safe, cost-effective biochar modification and activation should advance its use in pollutant remediation and nutrient management. Integrating biochar with compost, manure, biofertilizers, conservation agriculture, and precision nutrient management may provide synergistic benefits and warrants further investigation. In parallel, techno-economic analyses and life-cycle assessments should evaluate





production costs, energy efficiency, feedstock supply, and carbon sequestration potential. Finally, harmonized quality standards, regulatory frameworks, and supportive policies are essential to ensure biochar safety, facilitate commercialization, and promote its integration into climate-smart agriculture and sustainable land management.

## 10. Conclusion

Biochar is a multifunctional and promising tool for improving soil health, crop productivity, climate mitigation, and environmental sustainability. Produced through oxygen-limited thermochemical conversion of biomass, it can improve soil physical properties, nutrient retention, cation exchange capacity, soil organic carbon, and microbial activity, thereby supporting nutrient cycling and plant growth. Biochar also contributes to climate change mitigation through stable carbon sequestration and potential reductions in greenhouse gas emissions, while offering applications in heavy metal immobilization, wastewater treatment, pollutant adsorption, and waste valorization. Continued research, optimized production technologies, long-term field evaluation, quality standards, and supportive policies are therefore essential to maximize biochar's potential for sustainable agriculture, soil restoration, climate resilience, and environmental protection.

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# Export-Oriented Strategies in Agriculture and Allied Sectors

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India is one of the world's largest producers of agricultural commodities, yet its export potential remains underutilized. Export-oriented agriculture emphasizes producing high-quality, market-driven commodities that meet international standards, thereby increasing farmers' incomes, generating rural employment, and enhancing foreign exchange earnings (Government of India, 2018). Strengthening quality production, value addition, certification, infrastructure, and digital marketing can significantly improve India's global competitiveness (FAO, 2023). This article highlights key strategies to promote agricultural exports and unlock opportunities in allied sectors.

## Introduction

Agriculture plays a vital role in India's economy by providing livelihoods, ensuring food security, and contributing to national exports. India is a leading producer of cereals, fruits, vegetables, spices, dairy, fisheries, and livestock products. However, inadequate infrastructure, inconsistent quality, and limited awareness of international standards restrict export growth (APEDA, 2024). Export-oriented agriculture focuses on producing quality-assured commodities that satisfy global demand, helping farmers obtain premium prices while enhancing India's competitiveness in international markets (Government of India, 2018).

## Key Export-Oriented Strategies

### 1. Produce According to Market Demand

Farmers should cultivate export-oriented commodities such as basmati rice, spices, fruits, vegetables, medicinal plants, seafood, and organic products based on international demand and consumer preferences (FAO, 2023).

### 2. Ensure Quality Production

Adoption of Good Agricultural Practices (GAP), Integrated Pest Management (IPM), balanced

nutrient management, and hygienic harvesting improves product quality and ensures compliance with international food safety standards (FAO, 2023).

### 3. Promote Certification and Traceability

Certification systems such as Global G.A.P., Organic Certification, HACCP, and ISO 22000 enhance consumer confidence and facilitate access to international markets. Digital traceability systems further improve transparency throughout the supply chain (APEDA, 2024).

### 4. Encourage Value Addition

Processing agricultural produce into products such as fruit pulp, frozen vegetables, spice powders, dairy products, and ready-to-eat foods increases shelf life, minimizes post-harvest losses, and generates higher export earnings (Birthal et al., 2021).

### 5. Strengthen Farmer Producer Organizations (FPOs)

Farmer Producer Organizations enable aggregation of produce, quality standardization, collective marketing, and direct access to export markets, thereby improving farmers' bargaining power (Government of India, 2018).



## 6. Improve Post-Harvest Infrastructure

Investment in cold storage, grading facilities, warehouses, pack houses, and refrigerated transportation is essential for preserving product quality and reducing post-harvest losses (World Bank, 2023).

## 7. Utilize Digital Marketing

Digital platforms, e-commerce, online marketplaces, and mobile applications enable farmers and exporters to connect directly with international buyers while improving market transparency and efficiency (APEDA, 2024).

## 8. Promote Sustainable Agriculture

Organic farming, precision agriculture, efficient water management, and climate-smart agricultural practices enhance sustainability and meet the increasing global demand for environmentally friendly products (FAO, 2023).

## 9. Capacity Building

Agricultural extension services should train farmers on export standards, certification procedures, packaging, value addition, and market intelligence to improve export readiness (Kumar et al., 2022).

## Export Opportunities in Allied Sectors

India has considerable export potential beyond crop production.

- **Horticulture:** Fresh fruits, vegetables, flowers, and processed products (APEDA, 2024).
- **Dairy:** Milk powder, cheese, butter, and ghee.
- **Fisheries:** Shrimp, frozen fish, and value-added seafood.
- **Livestock:** Buffalo meat, poultry products, and animal feed.

- **Apiculture:** Honey and beeswax.

- **Floriculture:** Cut flowers and ornamental plants.

**Sericulture:** Silk yarn and silk products (Government of India, 2018).

## Role of Agricultural Extension

Agricultural extension plays a crucial role in promoting export-oriented agriculture by:

- Creating awareness about export opportunities.
- Training farmers on quality production and certification.
- Promoting Good Agricultural Practices.
- Disseminating market intelligence.
- Facilitating Farmer Producer Organizations.
- Supporting value addition and digital marketing (Kumar et al., 2022).

## Challenges

Major challenges include fragmented landholdings, poor cold-chain infrastructure, high logistics costs, inadequate processing facilities, stringent sanitary and phytosanitary standards, limited awareness of export procedures, and climate change impacts (World Bank, 2023; WTO, 2024).

## Way Forward

India should strengthen export clusters, promote Farmer Producer Organizations, invest in post-harvest infrastructure, encourage value addition, adopt digital technologies, and expand sustainable farming practices. Strong collaboration among research institutions, extension agencies, policymakers, and agribusinesses will further enhance India's agricultural export competitiveness (Government of India, 2018; APEDA, 2024).



### Conclusion

Export-oriented strategies can transform Indian agriculture into a globally competitive sector by emphasizing quality production, certification, value addition, efficient infrastructure, and sustainable farming practices. Allied sectors such as horticulture, dairy, fisheries, livestock, floriculture, and apiculture provide immense opportunities for export diversification. With effective policies, institutional support, and strengthened extension services, India can significantly increase agricultural exports, improve farmers' incomes, and contribute to sustainable economic growth (FAO, 2023).

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# Bone Health and Osteoporosis in Women: Building Strength for Life

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Bone health is a crucial but often overlooked aspect of women's well-being. Women are more vulnerable than men to osteoporosis due to hormonal changes, nutritional factors, and lifestyle choices. Osteoporosis is a condition that weakens bones and increases fracture risk. This article highlights the importance of bone health in women, risk factors for osteoporosis, preventive strategies, and modern treatment approaches.

## Introduction

Bones are the body's silent support system. Yet, they often go unnoticed until a fracture occurs. For women, bone health requires special attention, as hormonal changes during pregnancy, breastfeeding, and especially menopause can accelerate bone loss. Millions of women worldwide suffer from osteoporosis, also known as the "silent disease," which frequently goes untreated until a severe fracture occurs.

## Why Women Are at Higher Risk

- **Hormonal Influence:** Estrogen plays a protective role in maintaining bone density. The sharp decline in estrogen during menopause accelerates bone loss.
- **Smaller Bone Structure:** Women generally have smaller, thinner bones than men, making them more vulnerable to fractures.
- **Pregnancy & Lactation:** Nutritional demands of pregnancy and breastfeeding can deplete calcium reserves if not managed properly.
- **Longer Lifespan:** Women tend to live longer, and aging itself is a key risk factor for osteoporosis.

## Risk Factors for Osteoporosis in Women

- Family history of osteoporosis or fractures

- Early menopause or surgical removal of ovaries
- Vitamin D deficiency or low calcium intake
- Sedentary lifestyle and lack of weight-bearing exercise
- Smoking and excessive alcohol consumption
- Certain medications (like steroids, thyroid drugs)

## Signs & Symptoms

Often called a "silent disease," osteoporosis shows few early signs. Common indicators include:

- Back pain due to spinal fractures
- Loss of height over time
- Stooped posture (dowager's hump)
- Fragility fractures (hip, spine, or wrist) after minor falls

## Preventive Strategies for Women

### 1. Nutrition for Strong Bones

- **Calcium:** 1000–1200 mg calcium per day is required for adult women. This requirement can be met through taking dairy, leafy greens, fortified foods in everyday diet.





- **Vitamin D:** This is essential for calcium absorption. Sunlight exposure is good source of Vitamin D. Supplements can be given if required.
- **Protein:** Protein is important for muscle support and bone strength.
- **Magnesium & Vitamin K:** These are found in nuts, seeds, and green vegetables and required for good bone health.

## 2. Exercise & Lifestyle

Regular physical activity and healthy lifestyle habits play a crucial role in maintaining strong bones and preventing osteoporosis. Exercise helps stimulate bone formation, improve muscle strength, enhance balance, and reduce the risk of fractures.

- **Weight-bearing activities:** Among the most beneficial forms of exercise for bone health are weight-bearing activities such as walking, dancing, jogging, hiking, and climbing stairs. These activities require the body to work against gravity, placing gentle stress on the bones, which stimulates bone-building cells and helps maintain or increase bone mineral density.
- **Strength training:** This type of exercise includes activities such as lifting weights, using resistance bands, or performing body-weight exercises like squats and push-ups. When muscles contract against resistance, they exert force on the bones, stimulating bone growth and improving bone density.
- **Balance & flexibility exercises:** Balance and flexibility exercises are equally important, particularly for older adults who are at a greater risk of falls and fractures. Practices such as yoga and tai chi improve balance, coordination, flexibility, and body awareness. Yoga combines stretching, strengthening, and

controlled breathing techniques that enhance posture, muscle strength, and joint mobility. Tai chi involves slow, flowing movements that improve stability and coordination while reducing the risk of falls.

- **Avoid smoking & excessive alcohol:** Lifestyle choices also significantly influence bone health. Smoking is one of the major modifiable risk factors for osteoporosis because it interferes with the body's ability to absorb calcium, reduces blood flow to bones, and decreases the activity of bone-forming cells. Alcohol can impair calcium and vitamin D absorption, disrupt hormone balance, and decrease the body's ability to form new bone tissue. Therefore, avoiding smoking and limiting alcohol consumption are essential lifestyle measures for preserving bone strength and promoting lifelong skeletal health.

## 3. Regular Screening

- **Bone Mineral Density (DEXA Scan):** Recommended for women above 50 or earlier if risk factors exist.

## Treatment Options

- **Medications:** Bisphosphonates, hormone replacement therapy (HRT), selective estrogen receptor modulators (SERMs), and newer biologics.
- **Supplements:** Calcium and Vitamin D, especially post-menopause.
- **Lifestyle Interventions:** Nutrition, exercise, fall prevention measures.

## The Future of Bone Health in Women

Advances in osteoporosis care are making prevention and treatment more personalized and effective. Emerging therapies, including stem cell-based



treatments, bone-regenerating biologics, and smart wearable devices that monitor mobility and fall risk, offer new possibilities for bone health management. At the same time, awareness campaigns are encouraging women to adopt preventive measures early in life, helping reduce osteoporosis risk before menopause and older age.

### Conclusion

Strong bones are essential for maintaining women's independence, mobility, and overall quality of life. Osteoporosis can be largely prevented and effectively

managed through adequate nutrition, regular physical activity, healthy lifestyle habits, and timely health screenings. Prioritizing bone health throughout life not only reduces the risk of fractures but also supports long-term strength, functional ability, and healthy aging.

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# Soil Biological Health: The Living Foundation of Sustainable Agriculture

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A vital part of soil quality, soil biological health is important for maintaining both environmental sustainability and agricultural output. It includes the quantity, variety, and activity of soil fauna and microbes that power vital ecosystem functions like carbon sequestration, disease prevention, organic matter breakdown, and nutrient cycling. Plant development, soil structure, and resilience to external pressures are all supported by biologically healthy soil. However, soil biological communities around the world have suffered as a result of climate change, excessive chemical inputs, and intensive agriculture methods. Organic amendments, crop diversity, cover crops, conservation tillage, and the use of biofertilizer are examples of sustainable management techniques that can enhance soil biological health and restore ecosystem functioning. The significance of soil biodiversity, important biological health indicators, variables influencing soil biota, and management techniques for preserving resilient and productive agroecosystems are all highlighted in this article.

## 1.Introduction

A teaspoon of healthy soil contains more living organisms than the entire human population on Earth, making soil one of the most biologically diverse habitats on the planet. Plant growth, soil fertility, and ecosystem functioning are all supported by this hidden world of microbes and soil animals.

Many people refer to soil as the "living skin of the Earth" since it is the basis for agricultural output and nourishes almost all terrestrial life. Healthy soil is a dynamic ecosystem that is home to billions of bacteria, fungus, archaea, protozoa, nematodes, earthworms, and other soil species despite its seeming inertness. Together, these creatures break down organic materials, recycle nutrients, enhance soil structure, store carbon, and shield plants from

illness. Through their combined efforts, soil is transformed from a basic growing medium into a vibrant, self-sustaining ecosystem.

The idea of soil biological health has drawn more attention recently as a crucial aspect of overall soil health. In the past, the physical and chemical characteristics of the soil were primarily used to assess its quality. However, a rising body of research has shown that the biological aspect of soil is just as significant since microorganisms control numerous processes that affect agricultural production, soil fertility, and environmental sustainability (Bünemann et al., 2018). It is now acknowledged that the quantity, variety, and activity of soil organisms are trustworthy markers of a robust and healthy soil ecosystem.



In addition to promoting effective nutrient cycling, healthy soils also boost soil aggregation and water-holding capacity, improve carbon sequestration, and make agricultural systems more resilient to environmental pressures like pests and drought. Plant growth-promoting rhizobacteria (PGPR), mycorrhizal fungi, nitrogen-fixing bacteria, and phosphorus-solubilizing microorganisms are examples of beneficial microorganisms that are essential for increasing agricultural yield, boosting plant development, and improving nutrient availability (Wang et al., 2024). On the other hand, soil biological communities can be disrupted by intensive agriculture, excessive tillage, careless use of agrochemicals, residue burning, and climate change, which can result in soil degradation and decreased ecosystem functioning (Lehman et al., 2015).

Therefore, creating sustainable farming methods that increase output while preserving natural resources requires an understanding of the significance of soil biological health. This article addresses the function of soil organisms in sustainable agriculture, emphasizes the significance of soil biodiversity, describes the major indicators and factors influencing soil biological health, and provides useful management techniques for preserving resilient and healthy soils.

## 2. Soil Biological Health and Its Importance

The quantity, variety, and activity of living things found in soil as well as their capacity to support ecological processes are referred to as soil biological health. Bacteria, fungi, actinomycetes, archaea, protozoa, nematodes, earthworms, and other soil fauna are examples of these species. Collectively, they control soil aggregation, organic matter decomposition, nutrient cycling, and plant health. Because various microbial populations carry out specific ecological tasks, microbial diversity is especially significant. According to Delgado-Baquerizo et al. (2016), diverse microbial

communities enhance ecosystem multifunctionality and boost resilience against environmental challenges such salt, drought, and nutrient deficits. Therefore, crop production and environmental sustainability are supported by biologically sound soil.

## 3. Soil Biodiversity and the Soil Food Web

The biological basis of ecosystem functioning is soil biodiversity. A single gram of healthy soil is home to billions of microorganisms, forming a very dynamic and diverse ecosystem. The soil food web is a network that facilitates interactions between these creatures.

As main decomposers, bacteria and fungus break down organic materials and plant leftovers into simpler molecules. Nematodes and protozoa consume microbial populations and release nutrients that plants can use. Insects, termites, mites, and earthworms are examples of larger organisms that enhance soil structure and aid in the cycling of nutrients.

Nutrient availability, soil aggregation, water infiltration, and disease suppression are all improved by a balanced soil food web. According to research, more biodiverse soils have higher ecosystem stability and multifunctionality (Delgado-Baquerizo et al., 2016).

## 4. Indicators of Soil Biological Health

To assess the biological health of soil, a number of indicators are frequently employed (**Figure 1**). Microbial Biomass Carbon (MBC): Represents the living microbial component of soil organic matter and serves as a sensitive indicator of soil health.

Soil Respiration: Measures microbial metabolic activity through carbon dioxide evolution.

Enzyme Activity: Enzymes such as dehydrogenase, phosphatase, urease, and  $\beta$ -glucosidase are involved in nutrient cycling and indicate biological functioning of soil (Semenov *et al.*, 2025).



**Earthworm Population:** Earthworms are considered natural indicators of healthy soil because they improve aeration, aggregation, and nutrient availability.

**Microbial Diversity:** Greater microbial diversity generally reflects improved ecosystem stability and resilience.

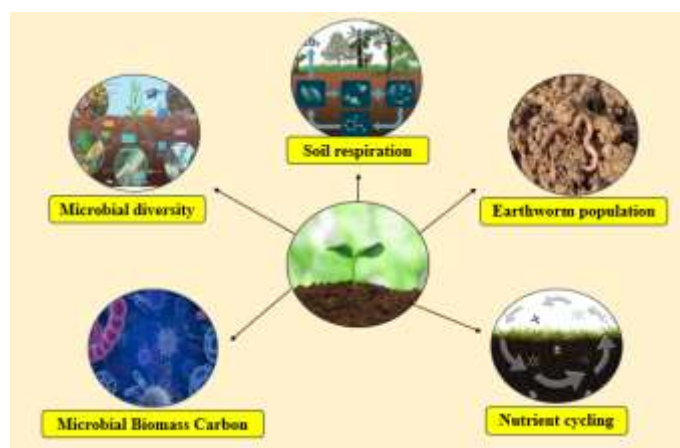


Fig 1: Indicators of Soil Biological Health

## 5. Factors Affecting Soil Biological Health

Several factors influence biological activity within soil ecosystems (**Figure 2**).

### Physical Factors

- Soil texture
- Moisture content
- Temperature
- Aeration and porosity

### Chemical Factors

- Soil pH
- Organic matter content
- Nutrient availability
- Salinity

### Biological Factors

- Root exudates
- Plant diversity
- Crop rotation

### Human Activities

Agricultural practices such as excessive tillage, residue burning, continuous monocropping, and indiscriminate use of pesticides and fertilizers can negatively affect soil microbial communities and reduce biological health (Lehman *et al.*, 2015).

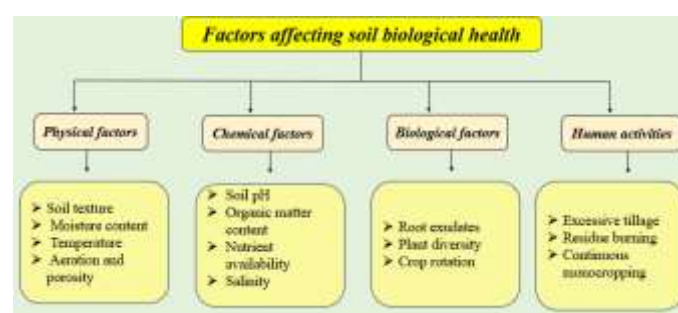


Fig 2: Factors affecting soil biological health

## 6. Role of Soil Organisms in Sustainable Agriculture

Numerous ecological services provided by soil organisms have a direct impact on agricultural productivity (Table 1).

### Nutrient Cycling

By breaking down organic materials, microorganisms provide nutrients that plants can absorb. Microorganisms that fix nitrogen and solubilize phosphorus are especially crucial for preserving soil fertility.

### Plant Growth Promotion

Plant growth-promoting rhizobacteria (PGPR) and mycorrhizal fungi are examples of beneficial microbes that enhance root development, nitrogen uptake, and plant stress tolerance (Wang *et al.*, 2024).

### Disease Suppression





Through competition and the synthesis of antimicrobial chemicals, several soil microbes inhibit plant pathogens, lowering the incidence of disease.

### *Carbon Sequestration*

In order to slow down climate change, microbial activity helps create stable soil organic matter and long-term carbon storage.

### *Ecosystem Resilience*

The capacity of soil ecosystems to endure environmental stressors and sustain productivity in the face of shifting climatic circumstances is enhanced by a diversified microbial community.

**Table1: Role of Soil Organisms in Sustainable Agriculture**

| Ecological Function           | Role in Sustainable Agriculture                                                                                                                                                  |
|-------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <b>Nutrient Cycling</b>       | Microorganisms in the soil break down organic debris and release nutrients that plants can use. Microbes that fix nitrogen and dissolve phosphorus contribute to soil fertility. |
| <b>Plant Growth Promotion</b> | Mycorrhizal fungi and plant growth-promoting rhizobacteria (PGPR) improve root growth, increase nutrient intake, and increase resistance to environmental stressors.             |
| <b>Disease Suppression</b>    | Through competition, antibiosis, and other biological interactions, beneficial microbes reduce soil-borne pathogens, lowering the prevalence of disease.                         |
| <b>Carbon Sequestration</b>   | Microbial activity promotes long-term carbon storage and                                                                                                                         |

|                             |                                                                                                                                                 |
|-----------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------|
|                             | mitigates climate change by helping to build stable soil organic matter.                                                                        |
| <b>Ecosystem Resilience</b> | Diverse microbial communities enhance soil resilience, production, and stability in the face of shifting climatic and environmental conditions. |

## 7. Strategies to Improve Soil Biological Health

Adopting sustainable soil management techniques is necessary to preserve the biological health of the soil.

### *Organic Amendments*

Applying farmyard manure, compost, vermicompost, green manures, and biochar increases microbial activity and gives soil microorganisms energy sources.

### *Crop Rotation and Diversification*

Diverse cropping systems enhance nutrient cycling and support beneficial microbial populations.

### *Cover Cropping*

Cover crops provide year-round microbial activity, lessen erosion, and boost organic matter inputs.

### *Conservation Tillage*

Reduced soil disturbance enhances soil structure and protects microbial habitats.

### *Biofertilizers*

Beneficial microorganisms included in biofertilizers increase soil biological activity and nutrient availability. Biofertilizer-based soil management techniques are now more successful due to recent developments in microbial biotechnology (Wang et al., 2024).



## 8. Future Perspectives

We now have a better grasp of soil microbial populations thanks to recent advancements in metagenomics and molecular methods. Researchers can now more precisely identify helpful bacteria and comprehend their ecological roles thanks to these technologies. Future studies should concentrate on enhancing biological markers for tracking soil health and creating climate-resilient soil management techniques (Semenov et al., 2025).

## 9. Conclusion

The living basis of sustainable agriculture is the biological health of the soil. Nutrient cycling, organic matter breakdown, disease prevention, and carbon sequestration are all regulated by diverse and active microbial populations. Long-term soil productivity and biological health can be greatly enhanced by sustainable methods such crop diversification, organic amendments, conservation tillage, and the use of biofertilizer. Food security, environmental sustainability, and climatic resilience all depend on protecting the living component of soil.

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## Making Every Advisory Count: Reinforcement as a catalyst for Agricultural Extension

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Agricultural extension has played a pivotal role in enhancing agricultural productivity by disseminating scientific knowledge and promoting improved farming practices. With the rapid advancement of agricultural technologies and digital information systems, advisory services have become more accessible than ever before. However, the adoption of recommended technologies by farmers continues to remain below expectations, indicating that information alone is insufficient to bring about sustained behavioural change. Farmers' decisions are influenced not only by technical knowledge but also by behavioural, social, psychological and institutional factors. In this context, reinforcement has emerged as an important complementary tool that strengthens the effectiveness of agricultural advisory services through continuous follow-up, timely reminders, motivation, problem-solving and confidence building. Reinforcement supports farmers throughout the decision-making and implementation process, thereby increasing the likelihood of sustained adoption of recommended practices. This article reviews the evolving role of advisory and reinforcement in the Indian agricultural extension system and discusses their significance in promoting sustainable agriculture. It also highlights the integration of behavioural science, digital technologies and human-centred extension approaches for improving technology adoption. The article concludes that combining advisory with systematic reinforcement can transform agricultural extension from a knowledge dissemination system into a behaviour-oriented support system capable of accelerating technology adoption, improving resource-use efficiency and strengthening the sustainability of Indian agriculture.

### Introduction

Agriculture continues to be the backbone of the Indian economy, supporting the livelihoods of nearly half of the country's population while ensuring national food and nutritional security. Over the past several decades, Indian agricultural research institutions have developed numerous improved crop varieties, resource conservation technologies, integrated nutrient management practices, climate-resilient production systems and digital agricultural innovations. Although these technologies possess immense potential to enhance productivity, profitability and sustainability, their impact largely depends on the extent to which they are adopted by farmers.

Agricultural extension has traditionally served as the bridge between research laboratories

and farmers' fields. Its primary objective is not merely to disseminate scientific information but to facilitate informed decision-making, enhance farmers' knowledge and skills and ultimately improve agricultural productivity and rural livelihoods. Anderson (2007) defined Agricultural Extension and Advisory Services (AEAS) as the collective network of organizations that support farmers by providing information, technical knowledge, problem-solving assistance and access to appropriate technologies for improving their livelihoods. In India, these services are delivered through the Indian Council of Agricultural Research (ICAR), State Agricultural Universities (SAUs), Krishi Vigyan Kendras (KVKs), Agricultural Technology Management Agency (ATMA), Departments of Agriculture, Farmer Producer



Organizations (FPOs), private agencies and increasingly through digital platforms.

During the last decade, agricultural extension has undergone a remarkable transformation with the introduction of mobile applications, artificial intelligence (AI)-based advisory systems, weather forecasting services, satellite-based crop monitoring, WhatsApp advisory groups and digital knowledge portals. These innovations have significantly expanded farmers' access to scientific information. However, despite this unprecedented availability of advisory services, adoption of several recommended agricultural practices continues to remain lower than expected.

This situation indicates that the challenge facing Indian agriculture today is no longer the lack of technologies or information. Rather, the greater challenge lies in helping farmers convert scientific knowledge into sustained behavioural change. In this context, agricultural extension needs to evolve from an information dissemination system to a behaviour change support system. Integrating advisory with reinforcement offers a promising approach for improving technology adoption and enhancing the effectiveness of extension programmes.

### **Agricultural Advisory Services: Foundation of Modern Extension**

Agricultural advisory services refer to the systematic process of providing timely, location-specific and scientifically validated recommendations that assist farmers in making informed decisions regarding crop production, natural resource management, livestock, horticulture and allied enterprises. These services aim to improve farm productivity, profitability, resilience and sustainability through continuous knowledge sharing and technical guidance.

Extension advisories are delivered through multiple approaches, including:

- Farm and home visits

- Farmer trainings and capacity-building programmes
- Frontline demonstrations
- Farmer field schools
- Radio and television broadcasts
- Printed literature and farm magazines
- Soil Health Cards and nutrient recommendations
- Kisan Call Centres
- Mobile SMS services
- WhatsApp and social media groups
- Mobile applications and AI-enabled advisory platforms

Modern advisory services are becoming increasingly personalized by integrating weather forecasts, remote sensing, market intelligence and digital decision-support tools. Such advancements have substantially improved the accessibility and timeliness of agricultural information.

However, advisory services alone often assume that once farmers receive scientific recommendations, they will naturally adopt them. Practical experience and behavioural research suggest otherwise.

### **Why Advisory Alone is Often Insufficient**

The adoption of agricultural technologies is a complex behavioural process rather than a simple transfer of information. Farmers' decisions are influenced not only by scientific recommendations but also by psychological, economic, social, institutional and environmental factors.

Research has consistently demonstrated that although economic returns remain important, several non-economic factors significantly influence farmers' decision-making. These include existing habits, risk



perception, labour availability, confidence in new technologies, previous farming experiences, social norms, peer influence, availability of inputs and trust in extension personnel. Consequently, receiving correct information does not necessarily result in behavioural change.

For example, farmers may fully understand the benefits of balanced fertilizer application, efficient irrigation scheduling or integrated pest management but continue following traditional practices because these methods are familiar, perceived as less risky or widely practiced within their communities. Similarly, many farmers intend to adopt improved technologies but postpone implementation due to uncertainty, lack of confidence or fear of economic losses.

Another limitation of conventional advisory systems is that they generally involve one-time communication. Farmers attend a training programme, receive printed recommendations or obtain advisory messages through digital platforms, but subsequent follow-up interactions are often limited. Without continuous engagement, farmers may forget recommendations, misunderstand technical information or gradually return to conventional practices.

This gap between awareness and adoption represents one of the major challenges confronting agricultural extension today.

### **Behavioural Dimensions of Agricultural Decision-Making**

Agricultural decisions are fundamentally behavioural decisions. Every season, farmers make numerous choices regarding crop selection, seed rate, fertilizer application, irrigation scheduling, pesticide use and resource conservation. These decisions are rarely based solely on technical recommendations.

Behavioural science suggests that individuals frequently rely on habits, experience and social influence while making decisions under uncertainty.

The Theory of Planned Behaviour (Ajzen, 1991) explains that adoption of new practices depends upon three important factors: favourable attitude towards the practice, perceived social expectations and confidence in one's ability to successfully implement the recommended technology. Unless these behavioural determinants are addressed, extension advisories may not translate into actual adoption.

Similarly, behavioural economics demonstrates that people often prefer familiar practices over unfamiliar alternatives, even when scientific evidence supports change. Farmers, like all individuals, are influenced by cognitive biases, perceived risks and immediate practical considerations. Therefore, expecting behavioural change through information alone may not always be realistic.

Learning theories also emphasize that behavioural change is a gradual process requiring repeated interaction, feedback and encouragement. Knowledge acquisition represents only the first stage; reinforcement and continuous motivation are essential for sustaining new behaviours over time.

These behavioural insights highlight the need to redesign agricultural extension programmes beyond traditional information transfer models. Rather than viewing farmers simply as recipients of technical recommendations, extension systems must recognize them as active decision-makers whose behaviour evolves through continuous learning, confidence-building and practical experience.

### **Reinforcement: A Behavioural Tool for Sustainable Agricultural Development**

Reinforcement is one of the fundamental principles of behavioural science and refers to any intervention that strengthens or increases the likelihood of a desired behaviour being repeated. In agricultural extension, reinforcement is not merely the repetition of advisory messages; rather, it is a systematic process of providing continuous encouragement, timely reminders, technical clarification and





motivational support that enables farmers to convert knowledge into sustained agricultural practices.

Unlike the conventional extension approach, where communication often ends after providing recommendations, reinforcement recognizes that adoption is a continuous process rather than a single event. Farmers frequently encounter uncertainties while implementing new technologies, including questions related to timing, input availability, changing weather conditions, market fluctuations and field-specific situations. Continuous follow-up during these critical stages increases farmers' confidence and minimizes the possibility of abandoning recommended practices.

Reinforcement can be delivered through various approaches such as periodic farm visits, telephone conversations, WhatsApp groups, mobile text messages, interactive voice response systems (IVRS), community meetings, farmer discussion groups, digital advisory platforms and peer learning. Timely appreciation of farmers who successfully adopt improved technologies and recognition through local extension programmes also act as positive reinforcement that encourages wider adoption within farming communities.

Research in behavioural science indicates that human behaviour rarely changes immediately after receiving information. Instead, repeated positive experiences, social encouragement and timely feedback gradually strengthen new behaviours until they become routine practices. Therefore, reinforcement should be viewed as an essential component of agricultural extension.

### **Digital Advisory and Human Reinforcement: A Complementary Approach**

The rapid advancement of information and communication technologies has transformed agricultural extension across the world. Mobile phones, internet connectivity, artificial intelligence, remote sensing, weather forecasting systems and digital advisory platforms have significantly

improved farmers' access to scientific information. Today, farmers can obtain crop advisories, weather forecasts, pest alerts, market prices and nutrient recommendations within seconds through various digital platforms.

Several initiatives such as Digital Agriculture Mission, Kisan Suvidha, Meghdoot, mKisan Portal, AI-based advisory platforms and mobile applications have strengthened the outreach of extension services in India. These technologies provide timely, location-specific and cost-effective information to millions of farmers simultaneously.

However, digital advisory alone cannot ensure behavioural change. Agricultural decisions are highly contextual and depend upon individual farm situations, farmers' experiences and local socio-economic conditions. Scientific recommendations often require interpretation, clarification and adaptation before implementation. Farmers also seek reassurance regarding the practical feasibility of recommendations before modifying their existing practices.

Therefore, digital technologies should complement rather than replace human extension services. While digital advisory improves the speed and accessibility of information dissemination, reinforcement through extension professionals provides trust, confidence and personalized support that digital platforms alone cannot offer. Integrating digital advisory with human reinforcement can substantially improve technology adoption while making extension services more efficient and responsive.

### **Role of Advisory and Reinforcement in Sustainable Agriculture**

The importance of advisory and reinforcement extends far beyond increasing crop yields. Sustainable agriculture requires continuous behavioural changes in resource management, environmental conservation and climate adaptation. Farmers are expected to adopt balanced fertilizer



application, efficient water management, integrated pest management, conservation agriculture, residue management, natural farming practices and climate-smart technologies. Most of these practices require long-term commitment rather than one-time adoption.

Soil health provides an excellent example. Healthy soils are the foundation of agricultural productivity and environmental sustainability. According to the Food and Agriculture Organization (FAO,2021), maintaining soil health is essential for ensuring food security, conserving biodiversity and achieving several Sustainable Development Goals (SDGs), including zero hunger, climate action and life on land. However, increasing fertilizer consumption, declining organic matter, nutrient imbalance and intensive cultivation have contributed to soil degradation in many parts of the country (FAO 2022).

To address these concerns, the Government of India has implemented several initiatives, including soil testing programmes and the Soil Health Card Scheme, to promote balanced nutrient management. These programmes generate valuable scientific recommendations regarding fertilizer application based on soil nutrient status. Nevertheless, several studies indicate that although farmers are increasingly aware of such recommendations, their adoption remains inconsistent due to inadequate follow-up, behavioural barriers, delayed access to information and limited technical support.

This situation illustrates an important lesson for agricultural extension. Generating scientific recommendations alone is insufficient unless farmers receive continuous guidance during implementation. Reinforcement bridges this gap by encouraging farmers to apply recommendations at appropriate crop stages, resolving practical constraints and strengthening confidence in improved practices.

The same principle applies to numerous agricultural interventions, including water conservation technologies, integrated pest management, climate-resilient agriculture, precision farming, crop diversification and natural farming. Continuous advisory coupled with systematic reinforcement significantly enhances the likelihood of sustained adoption and long-term environmental benefits.

### **Strengthening the Indian Agricultural Extension System**

As Indian agriculture moves towards digitalization, climate resilience and sustainable resource management, extension services must also evolve accordingly. Future extension programmes should shift their focus from merely disseminating information to facilitating behavioural change among farming communities.

Several measures can strengthen the effectiveness of advisory and reinforcement within the Indian extension system:

- Every advisory programme should include a structured follow-up mechanism instead of ending after information dissemination.
- Crop-stage-specific reminders should be incorporated into digital advisory systems to provide timely guidance during critical management operations.
- Artificial intelligence and digital platforms should be integrated with regular human interactions to ensure personalized problem-solving.
- Extension personnel should receive training in behavioural science, communication strategies and farmer psychology in addition to technical subject matter.
- Farmer feedback mechanisms should be strengthened so that advisory services remain demand-driven and responsive to local needs.



- Community-based learning approaches, farmer discussion groups and peer learning networks should be promoted to encourage collective behavioural change.
- Monitoring and evaluation of extension programmes should assess technology adoption and behavioural outcomes rather than simply counting the number of trainings, demonstrations or advisory messages delivered.

Such reforms would transform agricultural extension from an information delivery mechanism into a comprehensive behaviour change support system.

### Conclusion

Agricultural extension has played a pivotal role in India's agricultural transformation by connecting scientific research with farming communities. However, the rapidly changing agricultural landscape characterized by climate variability, natural resource degradation, digital transformation and increasing sustainability challenges demands a new approach to extension. Simply providing information is no longer sufficient to achieve widespread adoption of scientific farming practices. The integration of advisory and reinforcement represents the next evolution of agricultural extension in India. By combining the strengths of modern digital technologies with personalized human support, extension systems can improve technology adoption, strengthen natural resource management, enhance

climate resilience and contribute significantly to sustainable agricultural development. As Indian agriculture progresses towards achieving national development goals and the Sustainable Development Goals, advisory and reinforcement together can serve as powerful instruments for building a more productive, resilient and environmentally sustainable agricultural sector.

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## Sowing Innovation: The Rise of Agri-Startups in India's Decade-Long Startup Journey

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With more than two lakh DPIIT-recognized firms by December 2025, India's startup ecosystem has developed over the last ten years from a policy initiative to one of the biggest in the world. Alongside initiatives like AIM, NIDHI, GENESIS, and TIDE 2.0, which have increased funding, mentorship, and incubation support into Tier-II and Tier-III cities, this article charts the development of Startup India. A special emphasis is placed on agri-startups, which continue to struggle with issues including poor mentorship, restricted market access, insufficient seed investment, and underdeveloped incubation infrastructure. The article positions agri-startups as important forces behind India's inclusive, innovation-led economic future toward Viksit Bharat 2047 by highlighting pathways for sustainable growth, such as digital rural infrastructure, research incentives, stronger incubation centers, and curriculum reform in agricultural education, based on NAAS (2022) recommendations.

### Startup:

The Oxford Dictionary defines startup as “a newly established business” while according to Merriam-Webster, startup means “the act or an instance of setting in operation or motion” or “a fledging business enterprise”. At present the word startup can be defined in several manners and according to Investopedia, “a startup is a young company that is just beginning to develop. Startups are usually small and initially financed and operated by a handful of founders or one individual. These companies offer a product or service that is not currently being offered elsewhere in the market, or that the founders believe is being offered in an inferior manner”.

According to Department of Industrial Policy and Promotion (DIPP), an entity shall be considered as a Startup

- Up to 10 years from the date of its incorporation.

- Incorporated as a private limited company or registered as a partnership firm or a limited liability partnership.
- Turnover should be less than INR 100 crores in any of the previous financial years
- Working towards innovation/ improvement of existing products, services and processes and should have the potential to generate employment/ create wealth.
- An entity formed by splitting up or reconstruction of an existing business shall not be considered a "Startup".

### Different stages of development of Start-up: (Kumar *et al.* 2022)

**Idea generation:** Entrepreneurial ambition is the source of idea generation. Product or service idea for a market that is large enough. Some initial business models are created that generate revenue. At this stage a single or group of individuals exists and team structure and commitment are not yet made.



**Concept development:** At this stage the mission and vision of the startup is set along with the initial strategy. A core team comprising of the co-founders, ownership plans, rights, are established.

**Commitment:** The founding team is comprised of group of committed individuals having a balance of skills and values. The development of a minimum viable product is done to test the idea of the business. Agreement between the co-founder that is the shareholder agreement is done for a period of three years initially. Commitment among them is done regarding resources and time.

**Validation:** This is considered to be the most important stage by the customers, angel investors. Brand positioning and product strategy is developed while attracting potential series of venture capital investments. Key performance indicators are identified at the beginning. At this stage most of the start-ups fail.

**Scaling up:** At this stage focus is on key performance indicators to increase the number of users, clients, and revenues in the target market. Series A funding is received at this stage. Recruitment and human resource development is done along with improving the quality and product delivery to the target audience.

**Establishment of start-up:** The company is now on a growth streak and expected to continue its journey in the coming time. It has now become easier to attract funding and customers. At this stage an investor may exit or decide to continue to work with the company.

**Sources of funding for start-ups: (Kumar *et al.* 2022)**

**Personal investment:** Here the founder himself invest in the start-up. It is inexpensive and enables him to exercise maximum control over the business. Friends and family members can contribute

here. Interest rate and repayment programme are flexible as compared to a regular loan when borrowed from friends and relatives. But this way of receiving fund can be more stressful if the business becomes difficult.

**Angel investors:** These are individual investors who lend their money for early start-ups. Where venture capitalists manage the fund of many investors, angel investors lend their own money. During the early period when the start up is struggling for fund can get benefit from angel investors.

**Accelerators:** Accelerators provide financial support to the start-ups at their early stage and can make a difference in the success and failure of the business. Seed money is offered to start-ups in exchange for equity.

**Crowdfunding:** It is a method of raising funding from many people through the use of social media platforms or crowdfunding platforms. The contributors get equity share in the company.

**Micro venture capital firms:** As the name suggests, this venture capital has an asset value of less than 100 million dollars. Due to their low asset value, they are also known as 'seed stage funds'. These venture forms focus on start-ups at their seed stages.

**Corporate venture capital (CVC):** Corporate venture capital are multinational companies that invest in small and innovative start-ups in exchange for equity. They also provide strategic direction. When a start-up is associated with a big corporation its chances of success increases.

**Venture debt funds:** Financing start-ups with equity is expensive. In this regard the non-

banking financial institutions provide debt financing to VC-backed start-ups via a hybrid scheme known as venture debt funds. An equity warrants is used as a collateral to obtain venture debt financing.





**Government grants and funds:** Funding for Indian start-ups have gone beyond angel investors and venture capitalists. The start-ups enrolled in the start-up India programme gets a three years exemption on income tax along with 80 percent of cost of patents are rebated. The government has created a fund of funds through which loan is disbursed by SIDBI. An early-stage start-up fund, Start-up India Seed Fund, has also been also launched.

**Banks:** These are the conventional funding options for start-ups. They provide loans for

equipment, start-ups, working capital etc. Business loans are available at all stages. Many

NBFCs are involved in it.

### **Challenges faced by Agri-Startups:**

**Business Model:** Most of the agri-startups are mainly oriented towards production and marketing of agricultural produce on their own. They are unable to connect to the real problems of large number of stakeholders in the value chain to expand their businesses. Therefore, after initial success at small scale, they find great difficulty in scaling up the business.

**Lack of seed fund:** Agri-startups coming from humble background need funding support at initial stage to validate their ideas and develop minimum viable product (MVP). Small and fixed ticket-size grant opportunities are of very limited use for many of the agri-startups.

**Lack of mentorship:** The budding entrepreneurs in agriculture sector also face problems of right mentors, who can support them in networking, finding resources and developing proper business plan.

**Incubators' Competence:** The agribusiness incubators located with agricultural universities and other research organizations are also in early learning stage of learning curve. To provide needed support to

startups, the incubators need to have network of professionals with different domain knowledge. The incubators are also expected to provide testbed facilities for some of the startups. Overall professional competence with agribusiness incubators need to be boost up.

**Limited knowledge of available technology:** In agriculture sector, several commercially viable technologies (including digital technologies) are available with different research organizations, however the budding entrepreneurs either not aware of these technologies or they are not able to connect these technologies with the problems. (NAAS,2022)

### **INDIAN AGRICULTURE ON THE CUSP OF (R)EVOLUTION**

IBM Institute for Business Value and Oxford Economics found that 90% of Indian startups fail within the initial five years of their set-up. The lack of innovation is the main reason. However, in 2021, India has moved to 46th in the Global Innovation Index. However, several startups in the agri-sector are finding it difficult to scaleup the operation at the pan- India level. Different stakeholders attribute different factors to the lack luster growth and performance of agri-startups in India. The agri-food system will continue to remain a pivot of the economy for obvious reasons, like the growing demand for food due to population growth, demand for quality and variety of foods due to demographic changes and urbanization, challenges of climate change, digital and internet penetration, and evolution of new-age technologies. Although smallholding and slow technological development have kept precision farming a distant dream so far, Indian agriculture seems to be ready for its next digital agriculture revolution. Agriculture 4.01 would enable 'the Internet of Farming'- the intelligent use and analysis of data applied to the whole value chain, resulting in reduced costs, boosting farm income, and improving quality with end-to-end traceability. According to estimates, there are 600-700 agritech



startups in the country that use AI, machine learning, the internet of things, etc., to provide services to farmers. Digitally literate next- generation Indian farmers will simultaneously navigate the different farm and non-farm activities to augment their income.

In the backdrop of Agriculture 4.0, some of the challenges need to be addressed to create a culture for startups and enable an environment for new-age startups in the agriculture sector. Currently, the sector needs transformation focusing on digitalization, talent, sustainability, and business model. To accomplish this, a robust startup ecosystem has to play a vital role by

- creating the right mindsets and cultures in the agricultural research and educational institutes/universities to promote agri-startups,
- dynamic course curriculum of agricultural universities to give exposure to startups at an early stage and give adequate support to the interested students and faculty,
- encouraging inter-disciplinary and multi-disciplinary approach in agricultural education and research for making affordable innovative and efficient technologies for farmers and other stakeholders,

- building of common data platform as public good infrastructure about the research products, geospatial information, market, production, etc.,
- setting up a robust incubation system with needed infrastructure and competent work force to provide handholding support to the startups,
- involving corporates in the startup ecosystem,
- financing for working capital at the early stage of agri-startups. (NAAS, 2022)

### Key Sectors in Agri Startups

The sector-wise distribution of agri-startups in India (Startup India, 2024) shows that Agri-

tech dominates with 42%, indicating a strong shift toward technology-driven solutions such as digital platforms, AI, IoT, and precision farming. Food processing (17%) and organic agriculture (15%) also hold significant shares, reflecting growing emphasis on value addition, sustainability, and health-conscious consumption. In contrast, sectors like dairy farming (4%), horticulture (4%), and fisheries (2%) have relatively lower representation, suggesting untapped opportunities for innovation and investment. Overall, the data highlights India's transition from traditional farming practices to a more technology-oriented and market-linked agricultural ecosystem.

### Government Initiatives

| Initiative                    | Ministry/ Launched By | Objective                               | KEY FEATURES/ BENEFITS                                                      |
|-------------------------------|-----------------------|-----------------------------------------|-----------------------------------------------------------------------------|
| Atal Innovation Mission (AIM) | 2016, NITI Aayog      | Promote innovation and entrepreneurship | 2750 crore (till Mar 2028); supports schools, startups, research & industry |



|                                      |                 |                                        |                                                                                 |
|--------------------------------------|-----------------|----------------------------------------|---------------------------------------------------------------------------------|
| Atal Tinkering Labs                  | AIM             | Foster innovation among school student | 10.000+ labs, 733 districts, AI, Iot, Robotics, 3D printing; 1.1 crore students |
| Community Innovator Fellowship (CIF) | AIM, UNDP India | Grassroots entrepreneurship            | 1-year fellowship at Atal Community Innovation Centre                           |
| Youth CO Lab                         | AIM             | Youth-led innovation and SDGs          | National dialogues, incubation, National Innovation Challenges                  |
| AIM:2.0                              | 2024            | Scale innovation ecosystem             | LIPI, Frontier program, Human capital, Deeptech reactor, global collaborations  |
| GENESIS                              | 2022, MeitY     | Support deep-tech startups             | 490 crore; 1,600 startups in tier – II & Tier-III cities                        |
| MeitY Startup Hub (MSH)              | 2016, MeitY     | Strengthen tech startup ecosystem      | Supports 6,148+ startups, 517+ incubators, 329+ labs (Dec 2025)                 |
| TIDE 2.0                             | 2019, MeitY     | Promote ICT startups                   | Supports AI, IoT, Blockchain technology, Robotics through 51 incubators         |
| NIDHI                                | 2016, DST       | Convert innovations into startups      | 12000+ startups, 175+ TBIs, 1.3 lakh jobs, 1,100+ Ips                           |
| SVEP                                 | 2015, DAY-NRLM  | Promote rural entrepreneurship         | 3.74 lakh enterprises supported: improves rural livelihood                      |
| ASPIRE                               | 2015, MoMSME    | Rural innovation & incubation          | LBIs; grants up to 1 crore (govt) & 75 lakh (private)                           |
| PMEGP                                | 2008, KVIC/MSME | Self employment & micro enterprises    | Subsidy: 15-35% Project limit: 50 lakh (manufacturing), 20lakh (services)       |

### Startup India

Startup India is a flagship initiative launched by the Government of India on 16th January, 2016 to build a strong eco-system for nurturing innovation and startups in the country which will drive economic growth and generate large scale employment

opportunities. The Government through this initiative aims to empower startups to grow through innovation and design. The Standup India scheme was launched on 5th April, 2016 to facilitate bank loans from Scheduled Commercial Banks (SCBs) between Rs.10 lakh to Rs.1 Crore to at least one Scheduled Caste (SC) or Scheduled Tribe (ST) and



one woman per bank branch for setting up a greenfield enterprise in trading, services or manufacturing sector. The scheme is expected to benefit at least 2.5 lakh borrowers. Each enterprise will provide jobs depending on the nature of its operation.



The salient features of Startup India are as follows:

### **Simplification and Handholding**

- Simple Compliance Regime for startups based on Self-certification
- Launch of Mobile app and Portal for compliance and information exchange
- Startup India Hub to handhold startups during various phases of their development
- Legal support and fast-tracking patent examination at reduced costs
- Relaxed norms of public procurement for startups
- Faster exit for startups

### **Funding support and Incentives**

- Providing funding support through a Fund of Funds with a corpus of Rupees 10,000 crore
- Credit guarantee fund for startups
- Tax exemption on capital gains invested in Fund of Funds
- Tax exemption to startups for 3 years

### **Industry-Academia Partnership and Incubation**

- Organizing Startup Fests to showcase innovations and providing collaboration platforms
- Launch of Atal Innovation Mission (AIM) with Self –Employment and Talent Utilization (SETU) Program of NITI Aayog
- Harnessing private sector expertise for setting up incubators
- Setting up of 7 new research parks modeled on the Research Park at IIT Madras
- Launching of innovation focused programs for students.
- Annual Incubator Grand Challenge to promote good practices among incubators.

### **Credit Guarantee Fund**

The initiative provides for creating a credit guarantee fund for startups through Small

Industries Development Bank of India (SIDBI) with a Corpus of Rs.500 crore per year

for the next four years.

With this Action Plan the Government intends to accelerate spreading of the startup

movement:



- From digital/technology sector to a wide array of sectors including agriculture, manufacturing, social sector, healthcare, education, etc.; and
- From existing tier 1 cities to tier 2 and tier 3 cities including semi-urban and rural areas.
- The progress on the action points of the Startup India Action plan is Annexed.
- The Action Plan envisages setting up of 7 New Research Parks modeled on the Research Park at IIT Madras at IITs in Guwahati, Hyderabad, Kanpur, Kharagpur, Bangalore, Gandhinagar and Delhi and setting-up/scaling-up of 18 Technology
- Business Incubators (TBIs) at NITs/IITs/IIMs etc. as per the funding model of Department of Science and Technology. Startups will be able to access the facilities of the Research parks and Incubators and also receive the required support to give shape to their ideas.

### **Creating ecosystem for startups sustainability (NAAS,2022)**

**Startup India Initiative:** To overcome many pain points of startups, Government of India has launched Startup India Initiative wherein it tries to bring in most of the startups on one platform as well as identifying and enrolling them for benefits of different schemes like tax exemption, government procurements, financial access (seed fund) etc. Mentors, incubators and accelerators need to educate the startups for boarding the platform to reduce the risk. This ecosystem is sector agnostic. This ecosystem development partially fulfils the need of the startups.

**Provision of market access to agri-startups:** The major hurdle in growth of startup is market access. Innovation needs to be matched with proper markets. Collaborative work in Startups in emerging economies is determined by awareness of the role of

the environment, the size of the market and the context where the market is developing. For effective decision-making, the government should stimulate these companies in joint effort to continue exploring different interactions among all stakeholders, which allow a market for mutual benefit between company and farmers.

**Recommendations:** The suggestions for sustainable agri-startups in India are: (NAAS,2022)

### **1. Establishing a Startup Sustainability Ecosystem**

- Use the Startup India Initiative to unite startups for early investment, procurement advantages, and tax breaks.
- Encourage cooperation between startups, farmers, and stakeholders to increase market access.
- Make sure businesses receive expansion capital (such as the agri-startup fund from Budget 2022–2023).
- To reduce the time needed for product creation, create digital infrastructure for rural data (soil, crops, market information) in the public domain.
- Create a pool of mentors and investors by state.
- Make a special website with information about funding sources, programs, incubators, registration procedures, and frequently asked questions.

### **2. Innovation and Entrepreneurship Research:**

- Provide incentives for academics and researchers to start their own businesses (such as the FIRE plan concept at IIT Delhi).
- Make sure research organisations offer attractive terms for obtaining and validating agri-technologies.





### 3. Fortifying Incubation Facilities:

- Establish a Business Incubation Center at each research and educational institution (with centralised supervision, for example, across ICAR's more than 100 institutes).
- Staff centers with experienced, driven employees with expertise in entrepreneurship support.
- To de-risk innovations, provide sufficient, high-velocity catalytic investment (two to three years).
- Keep your governance structure open to facilitate prompt, high-quality decision-making.

### 4. Changing Agricultural Education to Promote Innovation

- Create innovation hubs at agricultural colleges and promote startup internships.
- Provide student-specific optional courses on innovation and entrepreneurship.
- After year three, give students who take risks the opportunity to pursue an entrepreneurial break or exit with academic credit and fellowship funding.

### Looking Ahead: A Future Built on Innovation & Extension

As India marks a decade of the Startup India Initiative, the country's startup ecosystem stands at an inflection point- moving decisively from rapid expansion to sustainable scale and deeper integration with the real economy. A decade on, India's startup ecosystem represents not merely scale, but structural transformation built on demographic advantage, digital public infrastructure, and a sustained reform

agenda. Startups are now embedded across priority sectors, driving innovation, employment generation, and global market integration. As India advances towards a \$7.3 trillion economy by 2030 and the broader vision of Viksit Bharat 2047, startups are poised to remain central to the country's development trajectory serving both as catalysts of growth and as enduring symbols of India's future-ready, innovation-led economic model.

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# Digital Green: Bridging Tradition and Technology - When Farmers Teach Farmers

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## Introduction

Agriculture continues to play a vital role in sustaining rural livelihoods and ensuring food security for millions of people worldwide. Despite its importance, farmers often face significant challenges in accessing accurate, timely, and location-specific agricultural information. Traditional agricultural extension systems, while essential, frequently encounter limitations such as inadequate numbers of extension workers, insufficient financial resources, and difficulties in reaching remote and geographically dispersed farming communities. As a result, many farmers are unable to benefit from the latest agricultural innovations, best management practices, and market information needed to improve productivity and income.

In recent years, digital technologies have emerged as powerful tools for overcoming these challenges and strengthening agricultural extension services. By leveraging information and communication technologies, extension agencies can deliver knowledge more efficiently and reach a larger number of farmers. Among the notable digital extension initiatives, Digital Green has gained widespread recognition for its innovative and participatory approach. Digital Green integrates technology with community engagement by producing and disseminating locally relevant agricultural videos featuring farmers from the same communities. This approach enhances trust, encourages peer learning, and improves the adoption of recommended practices. Through its combination

of digital tools, community participation, and data-driven monitoring, Digital Green has demonstrated how technology can effectively complement conventional extension systems and contribute to sustainable agricultural development.

## What is Digital Green?

Digital Green is an innovative non-profit organization founded in 2008 with the aim of enhancing the livelihoods of smallholder farmers through the use of digital technology and participatory extension approaches. (Gandhi et al., 2009). The organization leverages information and communication technologies, including digital videos, mobile applications, and data-driven tools, to facilitate the effective dissemination of agricultural knowledge and best practices among farming communities.

The core philosophy of Digital Green is based on the concept of **“farmers learning from farmers.”** (Bentley et al., 2014). Rather than depending exclusively on external experts, the organization creates locally relevant video content featuring farmers from the same community who successfully implement recommended agricultural practices. These videos showcase practical demonstrations, experiences, and solutions that are familiar to local audiences.

The videos are screened during community meetings and group discussions within villages, enabling farmers to learn in an interactive and participatory environment. Because the information



is presented by fellow farmers in local languages and cultural contexts, it is often perceived as more trustworthy, understandable, and applicable. This peer-learning model not only improves knowledge sharing but also encourages the adoption of improved agricultural practices, thereby contributing to increased productivity, income, and overall rural development.

### How Does Digital Green Work?

Digital Green follows a participatory and technology-enabled approach to disseminate agricultural knowledge among farming communities. The process typically involves the following steps:

1. **Selection of Relevant Practices:** Agricultural experts and community members identify farming practices that are suitable and beneficial for local conditions.
2. **Creation of Educational Videos:** Short videos are produced featuring local farmers, extension personnel, and successful practitioners demonstrating recommended techniques and innovations.
3. **Community-Based Video Screenings:** These videos are shown to groups of farmers in villages through organized viewing sessions conducted by trained facilitators.
4. **Interactive Learning and Discussion:** After each screening, farmers engage in discussions, ask questions, and share experiences to better understand and evaluate the showcased practices.
5. **Follow-up and Impact Assessment:** Feedback is gathered from participants, and adoption of the promoted practices is monitored to assess effectiveness and improve future extension activities.

### Major Initiatives of Digital Green

#### 1. Community Video-Based Learning

Digital Green develops short, locally relevant videos that demonstrate improved agricultural practices, livestock management techniques, nutrition interventions, and livelihood opportunities. These videos are screened in villages by trained facilitators to encourage interactive learning and knowledge sharing among farmers.

#### 2. Mobile Advisory Services

The organization leverages mobile technology to provide farmers with timely and practical information on crop production, weather forecasts, pest and disease management, and market-related updates, enabling them to make informed farming decisions.

#### 3. Nutrition and Health Awareness Programs

In addition to agricultural extension, Digital Green promotes awareness about balanced nutrition, maternal and child health, hygiene, and sanitation practices to improve the overall quality of life in rural communities.

#### 4. Empowering Rural Women

Digital Green places a strong emphasis on the inclusion of women by implementing programs that enhance their access to information, build their skills and confidence, and encourage their active participation in agricultural and household decision-making processes.

### Benefits of Digital Green

#### 1. Higher Adoption of Improved Agricultural Practices

Digital Green promotes learning through peer-to-peer knowledge exchange, where farmers observe and learn from fellow farmers who have successfully implemented recommended practices. This approach



builds trust and credibility, leading to higher adoption rates of agricultural technologies and innovations.

## **2. Cost-Effective Agricultural Extension**

By utilizing video-based learning and digital communication tools, Digital Green can reach a large number of farmers efficiently and economically. This reduces the costs associated with traditional face-to-face extension services while maintaining the quality and effectiveness of information delivery.

## **3. Improved Access to Agricultural Knowledge**

The platform enables the rapid dissemination of relevant and practical agricultural information across different villages and regions. Farmers gain timely access to knowledge on crop management, livestock care, natural resource management, and other important farming practices.

## **4. Greater Community Engagement and Participation**

Digital Green actively involves local communities in the creation, dissemination, and discussion of extension content. This participatory approach ensures that information is context-specific, culturally appropriate, and more readily accepted by farmers.

## **5. Enhanced Livelihoods and Food Security**

The adoption of improved agricultural practices contributes to increased farm productivity, higher household incomes, and more efficient use of resources. As a result, farming families experience improved livelihoods, greater economic resilience, and enhanced food and nutritional security.

## **6. Empowerment of Rural Communities**

By encouraging local leadership and farmer-to-farmer learning, Digital Green helps strengthen community capacity, fosters knowledge sharing, and promotes sustainable rural development.

## **Role of Digital Green in Agricultural Extension**

Digital Green is a notable example of modern agricultural extension that effectively combines **Information and Communication Technologies (ICTs)** with participatory and community-based approaches. It enhances the effectiveness of extension services by making agricultural information more accessible, engaging, and relevant to farmers. The initiative aligns closely with fundamental extension principles such as experiential learning, farmer participation, local leadership development, and community empowerment.

By promoting farmer-to-farmer knowledge exchange through locally produced videos, Digital Green encourages active learning and increases the credibility of extension messages. Its participatory approach ensures that farmers are not merely recipients of information but active contributors to the learning process. Furthermore, Digital Green demonstrates the potential of digital technologies to strengthen and complement conventional extension systems. (FAO, 2023). It helps overcome challenges related to limited extension personnel, geographical constraints, and resource shortages by enabling the efficient dissemination of agricultural knowledge to a larger audience. The model also serves as an effective link between research institutions, extension agencies, and farming communities, facilitating the transfer of innovations and best practices from laboratories and research centers to farmers' fields. As a result, Digital Green contributes to improving agricultural productivity, enhancing rural livelihoods, and promoting sustainable agricultural development.

## **Conclusion**

Digital Green has emerged as a powerful example of how technology can strengthen agricultural extension and rural development. By combining digital tools with community participation, it enables farmers to access practical knowledge in a simple and effective



manner. As agriculture becomes increasingly knowledge-intensive, initiatives like Digital Green will play a vital role in promoting sustainable farming, improving livelihoods, and building resilient rural communities. The future of agricultural extension lies not only in technology itself but in using technology to empower farmers and amplify their voices.

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# Climate Change and Water Resources: Concerns, Conservation and Sustainable Management

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## Introduction

Life, agriculture, industry, ecosystems, and economic growth all depend on water. Even though water covers almost 71% of the Earth's surface, only 2.5% of it is freshwater, and even less of it is easily accessible for human use. The world's water resources are under tremendous strain due to rapid population increase, urbanization, industry, and climate change. India relies heavily on rainfall and groundwater resources because it is an agrarian nation. Sustainable water resource management has become a significant concern due to the rising demand for water, irregular rainfall patterns, frequent droughts, floods, and falling groundwater levels. These problems have been made worse by climate change, which has changed the hydrological cycle and increased precipitation variability. Therefore, careful resource management is essential today, and this article outlined the difficulties, conservation, and sustainable management of water resources in the context of climate change.

**Water Resources and Their Importance:** Water resources include all sources of water that are useful or potentially useful to humans. These resources can be broadly classified into:

**1. Surface Water Resources:** Surface water includes rivers, lakes, reservoirs, ponds, streams, and wetlands. Major river systems in India such as the Ganga, Brahmaputra, Godavari, Krishna, and Narmada provide water for irrigation, domestic use, hydropower generation, and industrial purposes.

**2. Groundwater Resources:** Groundwater stored in aquifers is an important source of drinking and

irrigation water, especially in rural India. More than 60% of irrigation and about 80% of rural drinking water requirements in India are met through groundwater resources. However, excessive extraction has led to declining water tables in many regions.

**3. Rainwater:** Rainfall is the primary source of freshwater. In rainfed regions such as Vidarbha, effective utilization and conservation of rainwater are essential for enhancing agricultural productivity and ensuring water security.

## Visible Impact of Climate Change on Water Resources

Climate change significantly affects the quantity, quality, and distribution of water resources. The major impacts include:

**Altered Rainfall Patterns:** Climate change has resulted in changes in the timing, intensity, and distribution of rainfall. Many regions experience short-duration, high-intensity rainfall events leading to increased runoff and reduced groundwater recharge.

**Increased Frequency of Droughts and Floods:** Rising temperatures and changing precipitation patterns have increased the occurrence of extreme weather events such as droughts and floods. These events adversely affect agriculture, water availability, and livelihoods.

**Declining Groundwater Recharge:** Erratic rainfall and increased evapotranspiration reduce infiltration



and groundwater recharge, thereby lowering groundwater levels.

**Deterioration of Water Quality:** Increased temperatures, reduced stream flows, and extreme rainfall events can degrade water quality through sedimentation, nutrient loading, and contamination.

**Increased Water Demand:** Higher temperatures increase crop water requirements and domestic water consumption, thereby intensifying competition among different water users.

### **Water Resource Conservation and Management Strategies**

Sustainable management of water resources requires an integrated and holistic approach involving technological, institutional, and community-based interventions.

**1. Rainwater Harvesting:** Rainwater harvesting involves collecting and storing rainwater for future use. Rooftop harvesting, farm ponds, check dams, and percolation tanks are effective methods for augmenting water availability and groundwater recharge.

**2. Watershed Management:** Watershed management aims at conserving soil and water resources within a drainage basin. Integrated watershed development practices such as contour bunding, graded bunding, vegetative barriers, and gully control measures help reduce runoff, increase infiltration, and improve agricultural productivity.

**3. Efficient Irrigation Technologies:** Adoption of water-saving irrigation methods such as drip and sprinkler irrigation significantly improves water use efficiency. Precision irrigation practices ensure optimum use of available water resources.

**4. Groundwater Recharge:** Artificial recharge structures such as recharge pits, recharge shafts, percolation tanks, and recharge wells help replenish

depleted aquifers and improve groundwater sustainability.

**5. Recycling and Reuse of Water:** Treatment and reuse of domestic and industrial wastewater can substantially reduce freshwater demand. Recycled water can be utilized for irrigation, landscaping, and industrial applications.

**6. Crop Diversification and Climate-Resilient Agriculture:** Selection of drought-tolerant crops, adoption of climate-smart agricultural practices, and diversification of cropping systems can reduce water demand and enhance resilience to climate variability.

**7. Community Participation:** Active participation of local communities, water user associations, and stakeholders is essential for successful water resource management. Community-based approaches promote equitable distribution and sustainable use of water resources.

### **Water Resource Management Issues and Strategies**

Water resource management has become increasingly complex due to rapid socio-economic development and climate variability. Sustainable management requires addressing several interrelated issues affecting water availability, quality, accessibility, and equity.

**1. Increasing Water Scarcity:** In India, per capita water availability has declined substantially over the last few decades, leading to growing concerns regarding water security.

- Adoption of demand-side water management practices.
- Promotion of water-use efficiency in agriculture, industry, and domestic sectors.
- Implementation of water budgeting and water auditing.



- Encouragement of rainwater harvesting and storage systems.

**2. Groundwater Depletion:** Excessive and unregulated extraction has resulted in declining groundwater levels in many states. Overexploitation has also caused problems such as aquifer depletion, land subsidence, and deterioration of groundwater quality.

- Regulation and monitoring of groundwater extraction.
- Artificial groundwater recharge through recharge pits, percolation tanks, and recharge wells.
- Conjunctive use of surface and groundwater resources.
- Promotion of micro-irrigation systems and less water-intensive crops.

**3. Water Quality Degradation:** Contaminated water poses serious risks to human health and ecosystems. Major pollutants include; Nutrients (nitrogen and phosphorus), Pesticides and agrochemicals, Heavy metals, Pathogenic microorganisms and Industrial chemicals.

- Strict enforcement of water quality standards.
- Establishment of wastewater treatment facilities.
- Promotion of integrated nutrient and pest management.
- Continuous water quality monitoring and surveillance.
- Possibility of recycling and reuse of treated wastewater.

**4. Climate Change and Hydrological Uncertainty:** Potential impacts include; increased frequency of droughts and floods, altered river flow regimes,

reduced groundwater recharge and increased crop water requirements.

- Climate-resilient water resource planning.
- Development of early warning systems for droughts and floods.
- Adoption of climate-smart agricultural practices.
- Use of hydrological models and climate forecasting tools.

**5. Flood Management Issues:** Due to extreme rainfall events it is expected to increase the frequency and intensity of flood events.

- Construction and maintenance of flood control structures.
- Floodplain zoning and land-use regulation.
- Watershed-based runoff management.
- River training and embankment stabilization.
- Community-based flood preparedness and warning systems.

**6. Drought Management Challenges:** Rainfed regions such as Vidarbha are particularly vulnerable.

- Drought contingency planning.
- Construction of farm ponds and water harvesting structures.
- Adoption of drought-tolerant crop varieties.
- Efficient irrigation scheduling.
- Crop diversification and agroforestry systems.

**7. Sectoral Competition for Water:** Agriculture, domestic, industrial, and environmental sectors increasingly compete for limited water resources.



- Integrated Water Resources Management (IWRM).
- Prioritization of water allocation among sectors.
- Improvement in irrigation efficiency.
- Economic instruments such as water pricing.
- Stakeholder participation in water governance.

**8. Inefficient Irrigation Practices:** Conventional flood irrigation methods often result in substantial water losses through evaporation, seepage, and runoff.

- Adoption of drip and sprinkler irrigation systems.
- Precision agriculture and sensor-based irrigation scheduling.
- Deficit irrigation and supplemental irrigation practices.
- Irrigation advisory services based on weather forecasts.

**9. Ecosystem Degradation:** Wetlands, rivers, lakes, and other aquatic ecosystems provide essential ecosystem services such as water purification, groundwater recharge, and biodiversity conservation. Unsustainable exploitation has degraded many ecosystems.

- Protection and restoration of wetlands and river ecosystems.
- Maintenance of environmental flows in rivers.
- Catchment area treatment and afforestation.
- Sustainable watershed management practices.

## **Integrated Water Resource Management (IWRM)**

Integrated Water Resource Management (IWRM) is a process that promotes coordinated development and management of water, land, and related resources to maximize economic and social welfare without compromising ecosystem sustainability. The key principles of IWRM include:

- Coordinated management of surface and groundwater resources.
- Participation of stakeholders in decision-making.
- Equitable allocation of water among sectors.
- Protection and conservation of aquatic ecosystems.
- Adoption of demand-side management practices.



## **Conclusion**

Long-term water security depends on the sustainable management of water resources through groundwater recharge, watershed development, effective irrigation technology, rainwater collection, and integrated water resource management. In order to preserve water supplies for current and future generations, it will be essential to increase community involvement, encourage climate-resilient behaviours, and implement cutting-edge technologies. Achieving food security, environmental sustainability,



socioeconomic development, and water security all depend on sustainable water management.

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# Insects as Bioindicators: Nature's Tiny Guardians of Environmental Health

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## Introduction

Although insects are often regarded as agricultural pests or disease vectors, they perform numerous essential ecological functions that sustain life on Earth. They contribute to pollination, decomposition, nutrient recycling, biological control, and maintenance of ecosystem balance. Besides these well-known ecological services, insects also serve as bioindicators—living organisms whose presence, absence, abundance, or behaviour reflects the health of the surrounding environment (McGeoch, 1998). Their remarkable diversity, short life cycles, ecological specialization, and rapid response to environmental disturbances make them reliable indicators of changes in air, water, soil, and habitat quality (Chowdhury et al., 2023).

With increasing industrialization, urbanization, climate change, habitat destruction, and indiscriminate use of pesticides, monitoring environmental health has become more important than ever. Unlike conventional monitoring methods that require sophisticated instruments and high costs, insects provide a simple, cost-effective, and continuous means of assessing ecosystem health. Different insect groups reveal different environmental conditions—for example, butterflies indicate habitat quality, honey bees reflect pesticide and heavy metal contamination, dragonflies signal clean freshwater ecosystems, while ants, beetles, and termites provide valuable information on soil health

and ecological stability (Barganska et al., 2016; Cunningham et al., 2022; Rainio & Niemelä, 2003; Chowdhury et al., 2023). As nature's silent sentinels, insects provide early warning signs of environmental degradation and play a crucial role in biodiversity conservation, sustainable agriculture, and ecosystem management.

## What are Bioindicators?

Bioindicators are living organisms that provide information about the health of an ecosystem by responding to changes in environmental conditions. Their presence, absence, abundance, behaviour, or physiological changes can indicate pollution, habitat degradation, climate change, or ecological imbalance (McGeoch, 1998; Parmar et al., 2016). Since insects are highly sensitive to changes in their surroundings, they serve as excellent biological indicators of air, water, and soil quality. Monitoring insect populations enables scientists to detect environmental problems at an early stage and develop effective conservation and management strategies.

## Why are Insects Excellent Bioindicators?

Insects possess several characteristics that make them ideal bio indicators. They are highly diverse, abundant, widely distributed, and occupy almost every terrestrial and freshwater ecosystem. Their short life cycles and rapid reproduction allow them to respond quickly to environmental changes. Many insect species have specific habitat requirements,



making them sensitive to pollution, habitat disturbance, and climate change. In addition, insects are relatively easy to collect, identify, and monitor, making them a cost-effective tool for environmental assessment (McGeoch, 1998; Chowdhury et al., 2023).

### Major Bio Indicator Insects

Different insect groups indicate different aspects of environmental health. Butterflies reflect habitat quality and biodiversity, while honey bees reveal pesticide residues, heavy metal contamination, and air pollution through the analysis of honey, wax, and pollen (Barganska et al., 2016; Cunningham et al., 2022). Dragonflies, mayflies, stoneflies, and caddisflies are excellent indicators of freshwater quality because they are highly sensitive to pollution and low oxygen levels (Bonada, et al., 2006). Ants, ground beetles, dung beetles, and termites indicate soil health, land-use changes, and ecosystem stability, whereas chironomids and hoverflies are widely used to monitor aquatic pollution and landscape biodiversity.

| Insect group | Indicates                | Environmental application    |
|--------------|--------------------------|------------------------------|
| Butterflies  | Habitat quality          | Biodiversity conservation    |
| Honey bees   | Pesticides, heavy metals | Pollution monitoring         |
| Dragonflies  | Clean water              | Freshwater monitoring        |
| Mayflies     | Oxygen-rich water        | Water quality                |
| Stoneflies   | Low pollution            | River health                 |
| Caddisflies  | Water purity             | Aquatic ecosystem assessment |

|                |                  |                         |
|----------------|------------------|-------------------------|
| Ants           | Soil disturbance | Land-use monitoring     |
| Ground beetles | Habitat changes  | Agricultural monitoring |
| Dung beetles   | Soil fertility   | Nutrient cycling        |
| Termites       | Soil health      | Ecosystem functioning   |



### Applications in Agriculture and Environment

Bioindicator insects are increasingly being used to monitor environmental quality across agricultural, forest, freshwater, and urban ecosystems. In agriculture, pollinators, predators, parasitoids, ants, and dung beetles indicate soil fertility, pollination efficiency, biodiversity, and the impact of pesticide use. In forests, butterflies and beetles help assess habitat fragmentation and biodiversity loss, while aquatic insects are extensively used to evaluate river and lake health. In addition, insect-based monitoring helps detect climate change impacts, heavy metal contamination, and ecological restoration success, thereby supporting sustainable agriculture and biodiversity conservation (Da Rocha et al., 2010; Chowdhury et al., 2023).



### Modern Technologies in Insect Biomonitoring

Recent technological advances have greatly improved insect-based environmental monitoring. DNA barcoding enables accurate species identification, while environmental DNA (eDNA) helps detect insect diversity without direct sampling. Artificial intelligence (AI), machine learning, automated insect traps, drones, remote sensing, Geographic Information Systems (GIS), Smartphone-based insect identification applications and citizen science platforms such as iNaturalist are also contributing significantly to large-scale biodiversity monitoring and rapid environmental assessment. These modern tools enhance the accuracy, efficiency, and reliability of insect biomonitoring programmes, making them valuable for conservation and sustainable ecosystem management (Chowdhury et al., 2023).

### Conclusion

Insects are far more than crop pests or disease vectors; they are nature's tiny guardians that continuously monitor the health of our environment. Their sensitivity to pollution, habitat alteration, and climate change makes them reliable bio indicators for monitoring soil, water, air, and biodiversity. Conserving insect diversity not only protects ecosystem services such as pollination and natural pest control but also strengthens environmental monitoring programmes. Protecting insect diversity today is essential for conserving biodiversity, ensuring sustainable agriculture, and safeguarding environmental health for future generations.

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# A Comprehensive Analysis of Natural Farming Myths and Realities

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## Introduction

The trajectory of agriculture across the Indian subcontinent has arrived at a pivotal turning point, where the long-term consequences of the 1960s Green Revolution are being scrutinized against the imperatives of ecological balance and soil vitality.

During the mid-twentieth century, India faced a harrowing food security crisis, compounded by the detrimental remnants of colonial-era land policies that had severely weakened domestic agricultural capacity. Facing an urgent need to sustain a growing population—and compelled to import roughly 10 million tons of grain each year—the nation pivoted toward a model of high-input, industrial agriculture. This "Comprehensive Integrated Chemical Farming" framework prioritized sheer caloric volume, leveraging high-yielding variety (HYV) seeds supported by heavy applications of synthetic fertilizers and chemical agents.

While this paradigm successfully averted immediate famine, six decades of prioritizing synthetic inputs over traditional, regenerative organic practices have taken a significant toll. The relentless pursuit of maximum output at the expense of ecological synergy has resulted in widespread soil degradation, significant environmental erosion, and a deepening crisis in public health. Consequently, contemporary

agriculture is now tasked with reconciling the need for food security with the urgent necessity of restoring biological integrity to the land.



Fig.: 1- Chemical Agriculture: From Yield Dependency to Soil Health Crisis

## Comparative Framework of Agricultural Methodologies

Modern agriculture is defined by a spectrum of methodologies, each with a distinct approach to soil management, input requirements, and economic sustainability. To navigate the future of food production, it is essential to distinguish between the three primary systems: **Chemical Farming**, **Organic Farming**, and **Natural Farming**. While the latter two are frequently conflated, they represent fundamentally different philosophies and economic models.

| Feature            | Chemical Farming     | Organic Farming | Natural Farming                     |
|--------------------|----------------------|-----------------|-------------------------------------|
| Primary Philosophy | Maximizing yield via | Health-focused  | Nature-mimicking, cow-based systems |





|                           |                                   |                                          |                                         |
|---------------------------|-----------------------------------|------------------------------------------|-----------------------------------------|
|                           | synthetic inputs                  | chemical replacement                     |                                         |
| <b>Input Source</b>       | Industrial/Market-bought          | Market-bought or high-volume compost     | On-farm, indigenous resources           |
| <b>Economic Structure</b> | High input cost, debt-prone       | High cost (vermicompost, bio-pesticides) | Zero Budget / Minimal cost              |
| <b>Microbial Focus</b>    | Low (suppressed by synthetic NPK) | Moderate (added via external compost)    | High (cultivated via on-farm catalysts) |
| <b>Soil Physics</b>       | Compaction, salt accumulation     | Improved via external organic matter     | Improved via biological signaling       |
| <b>Certification</b>      | N/A                               | Strict, costly global standards          | Community-based, self-reliance          |

The contemporary practice of organic agriculture often risks mirroring the very structural flaws of the industrial chemical model it seeks to replace. By merely swapping synthetic substances for market-sourced biological alternatives such as commercially produced vermicompost, specialized bio-pesticides, and expensive botanical sprays the farmer remains trapped in a cycle of high production costs. Under this "input substitution" framework, the reliance on external supply chains persists, ensuring that the farmer's financial independence remains elusive.

In sharp contrast, **Natural Farming** epitomized by the Subhash Palekar Natural Farming (SPNF) methodology and the structural support of initiatives like the Gujarat government's ATMA project advocates for a paradigm shift toward "Zero Budget" agriculture. This approach fundamentally rejects the reliance on external markets, operating instead on the principle of on-farm self-sufficiency.

### Microbiology of the Indigenous Cow: The 1:30 Ratio

One of the most debated aspects of Natural Farming is the emphasis on indigenous (Desi) cows as opposed to cross-bred (Jersey or Holstein Friesian) cows. This is not a question of cultural bias but is

rooted in the microbial count and composition of the feces.

### Comparative Microbial Analysis

Scientific studies have determined the microbial count in the dung of different breeds of cows. One gram of Desi cow dung has 300 to 500 crore (3 to 5 billion) beneficial microbes. The microbial count in cross-bred cows is much lower, at 50 to 78 lakh (5 to 7.8 million).

| Cow Breed Group                               | Bacterial Population (per gram) | Key Microbial Phyla                                                     |
|-----------------------------------------------|---------------------------------|-------------------------------------------------------------------------|
| Indigenous (e.g., Gir, Sahiwal, Malnad Gidda) | 3 - 5 Billion                   | <i>Proteobacteria</i> ,<br><i>Actinobacteria</i> ,<br><i>Firmicutes</i> |
| Exotic/Cross-bred (e.g., HF, Jersey)          | 50 - 78 Million                 | Reduced diversity of nutrient solubilizers                              |

The Desi cow's gut acts as a superior bioreactor. The presence of microbes such as *Azotobacter* (nitrogen suppliers), *Pseudomonas* (phosphorus solubilizers), and *Bacillus silicus* (potash solubilizers) in high concentrations makes their dung the ideal starter for *Jiwamrutaa*





**MICROBIAL RICHNESS & THE "1:30" SCALING PRINCIPLE**

INDIGENOUS COW (e.g. Gir or Sahiwal breed)

COW DUNG

COW URINE

JEEVANMIT

1 DESI COW WASTE = INOCULATE 30 ACRES

30 ACRES

**ECONOMIC CATALYST: TRANSFORMING LIABILITIES INTO ASSETS**

**TRADITIONAL DAIRY MODEL**

FINANCIAL BURDEN

NON-NATURAL DAIRY MODEL

**NATURAL FARMING MODEL**

CORNERSTONE OF PRODUCTIVITY

SAVINGS: APPROX. 80,000 RUPEES/YEAR PER COW

AVOIDED INPUT EXPENDITURE

The exceptional microbial richness found in the waste of indigenous (*Desi*) cows serves as the foundation for the "1:30" scaling principle, a revolutionary approach to soil enrichment. Rather than functioning as a standard bulk fertilizer where volume must match acreage *Jeevamrit* operates as a powerful microbial culture. Consequently, the manure and urine produced by a single indigenous cow provide a sufficient concentration of beneficial microorganisms to inoculate up to 30 acres of land.

This paradigm shift in the input-to-area ratio transforms the *Desi* cow into an invaluable economic catalyst. In traditional dairy-centric operations, a dry or non-lactating cow is typically viewed as a financial burden; however, within this regenerative agricultural model, that same animal becomes the engine of farm productivity. By eliminating the necessity for synthetic fertilizers and pesticides, the presence of an indigenous cow can save a farmer approximately 80,000 rupees annually in avoided input expenditures, turning a perceived liability into a vital asset for economic and agricultural independence.

A pervasive narrative in agricultural circles suggests that abandoning chemical farming for Natural Farming will inevitably trigger a severe and prolonged decline in crop production. This outlook, however, is largely a byproduct of conflating two distinct methodologies: **Organic Farming** and **Natural Farming**. By failing to recognize the structural differences between these two systems, critics often misattribute the challenges of one to the potential of the other.

In Organic Farming, if a farmer removes chemical fertilizers but does not provide an immediate biological replacement, the soil (which has lost its inherent fertility) cannot support high yields.<sup>1</sup> However, in Natural Farming, the application of *Jiwamruta*, Bijamrut, and Mulching restores the biological cycle so rapidly that yield stability is often achieved from the very first season. The microbial intervention compensates for the lack of synthetic urea by fixing atmospheric nitrogen which comprises 78% of the air directly into the rhizosphere.

Nitrogen fixation is the primary mechanism through which Natural Farming maintains yields. The process can be represented as:

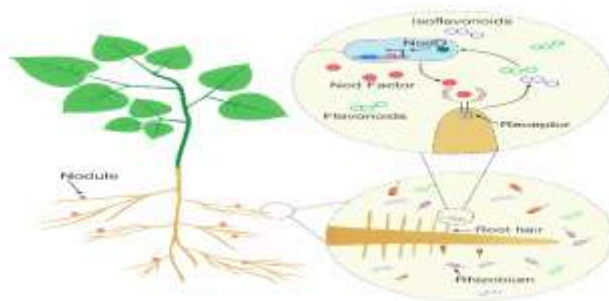
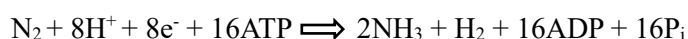


**Fig.:3** - Signal exchange in the legume-rhizobia interaction. Flavonoids and isoflavonoids secreted by legume roots activate the Nodulation protein D (NodD) transcription factor on compatible rhizobia inducing the transcription of *nod* genes, which are required for the

synthesis of Nod factors. Nod factors are perceived by receptors present in the plasma membrane of root cells, triggering the signaling pathway required for the development and infection of the nodule, where bacteria are allocated, and nitrogen fixation occurs.

This biological harvesting of nitrogen from the air eliminates the need for synthetic urea. Field experiences of practitioners in Gujarat have shown that with proper management of the four pillars, yield performance remains on par with or even exceeds chemical plots over time as soil health improves.

### Soil Health and Nutrient Availability

Another common misconception is that Natural Farming "exhausts" the soil because no nutrients are being **"added"** from outside. The reality is that the earth is a reservoir of nutrients. Plants derive approximately 95% to 98% of their structural components Carbon, Hydrogen, and Oxygen from air and water through photosynthesis. The remaining 1.5% to 2% of minerals are present in the soil in massive quantities but are often "locked" in insoluble forms due to chemical compaction. Natural Farming microbes solubilize these minerals, making them **"labyha"** (available) to the plants. Analysis of soil from Natural Farming plots often shows *higher* levels of available nutrients compared to chemical plots, despite the lack of external inputs.

### Agronomic Realities: Labor, Weeds, and Tillage

The practical management of a Natural Farm differs significantly from the conventional "control and conquer" approach to nature.



Fig 4 – Biological nitrogen fixation through natural

### The Myth of Excessive Labor

The preparation of *Jiwamrutaa* and the management of multiple crops are sometimes viewed as overly laborious. However, this must be weighed against the time and effort spent in the chemical system: standing in queues for subsidized urea, the health risks of spraying toxic pesticides, and the financial stress of managing debt. If a farmer keeps a cow and has a simple collection system for urine and dung, *Jiwamrutaa* can be prepared with minimal daily effort. Furthermore, the reduction in irrigation frequency and the natural suppression of weeds through mulching actually reduce the total labor requirement over the long term.

### Weed Management as Resource Opportunity

In chemical farming, weeds are seen as competitors that must be eradicated with herbicides.

**Natural Farming reclassifies weeds as a resource.** Weeds have deeper root systems than most crops and bring up micronutrients from lower soil layers. By cutting weeds before they flower and leaving them as mulch, the farmer "harvests" these nutrients for the main crop. **Leguminous weeds can contribute 12-15 kg of nitrogen per acre to the soil.** The focus is on "management" (ensuring the main crop remains taller to capture sunlight) rather than "eradication".

### The Reality of Tillage

For decades, agricultural universities and extension departments have recommended "deep ploughing" to improve aeration.

Natural Farming turns this logic on its head, advocating for **"minimum soil disturbance"**. Deep tillage disrupts the delicate fungal networks (Mycorrhizae) that are essential for nutrient uptake and allows precious soil carbon to escape as CO<sub>2</sub>. In Natural Farming, the role of tilling is outsourced to earthworms. Indigenous earthworms, stimulated by *Jiwamruta* and protected by mulch, create vertical



channels up to 15 feet deep. These "**biological tilling**" channels facilitate deep water infiltration and root growth without destroying the soil structure.

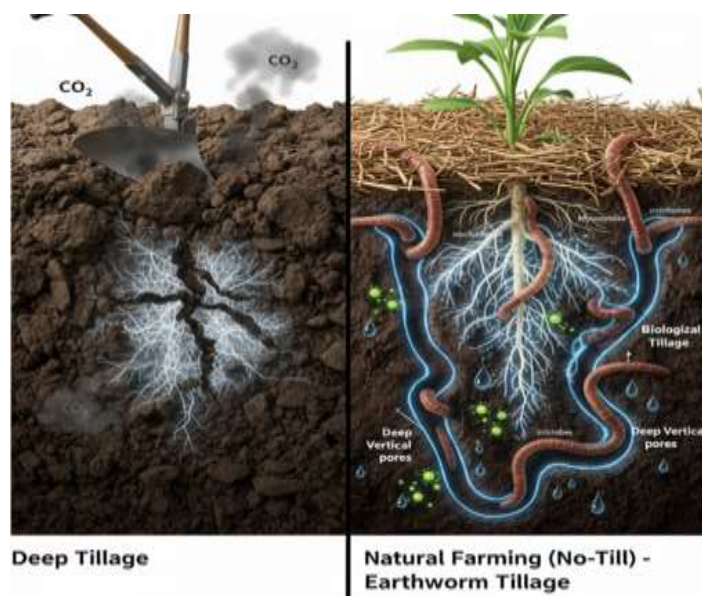


Fig : 5 The Reality of Tillage

## Socio-Economic Resilience and Environmental Impact

The shift to Natural Farming has profound implications for the socio-economic stability of rural India and the mitigation of global climate change.

### Debt Mitigation and Farmer Wellbeing

The "**Zero Budget**" aspect of Natural Farming is a direct response to the crisis of farmer suicides, which are primarily driven by debt. When the cost of production is slashed by 40% to 45% because inputs are generated on-farm, the net income of the farmer increases even if the market price remains stagnant.<sup>8</sup> This financial independence reduces the need for high-interest loans and makes the farm household more resilient to market volatility.

### Climate Resilience and Disaster Mitigation

Natural Farming practices significantly improve the climate-resilience of crops.

- **Drought Resilience:** The increased water-holding capacity and "**VAPSA**" condition allow crops to survive for longer periods without rainfall.
- **Flood Resilience:** Porous soil allows heavy rainwater to infiltrate deeply into the groundwater rather than causing surface runoff and crop lodging.
- **Carbon Sequestration:** By prohibiting residue burning and promoting mulching, Natural Farming significantly increases soil organic carbon (SOC), helping to mitigate atmospheric greenhouse gas concentrations.

## Human Health and Nutrition

The transition to chemical-free farming addresses the growing concern over pesticide residues in the food chain. Natural Farming products are reported to have higher nutritive value and better shelf life. By eliminating the use of synthetic NPK and poisonous sprays, the farm becomes a safe environment for the farmer and the consumer alike.

### Technical Synthesis: The "Myth vs Reality"

| Myth                        | Reality                                                   | Scientific Basis                                         |
|-----------------------------|-----------------------------------------------------------|----------------------------------------------------------|
| <b>Yield will drop.</b>     | Yield remains stable if <i>Jiwamruta</i> /Mulch are used. | Biological nitrogen fixation and mineral solubilization. |
| <b>It is too much work.</b> | Labor decreases over time as soil health improves.        | Reduced irrigation, weeding, and external procurement.   |
| <b>One needs many cows.</b> | One Desi cow is sufficient for 30 acres.                  | Microbial culture/inoculum vs. bulk                      |





|                                  |                                                       |                                                               |
|----------------------------------|-------------------------------------------------------|---------------------------------------------------------------|
|                                  |                                                       | fertilization.                                                |
| <b>Deep tillage is needed.</b>   | Minimum soil disturbance is better for biology.       | Earthworm-mediated biological tilling and Mycorrhizae health. |
| <b>Weeds kill the crop.</b>      | Weeds are a source of mulch and nitrogen.             | Nutrient harvesting from subsoil and leguminous N-fixation.   |
| <b>Earthworms attract pests.</b> | Earthworms improve soil physics; don't attract boars. | Vertical channel creation and gaseous exchange.               |

| Myth                                                        | Reality (Scientific Perspective)                                                                                                                               |
|-------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Natural farming means zero cost of cultivation.             | "Zero budget" refers to zero dependence on external credit, not zero expenditure. Costs like labor, irrigation, and preparation of inputs still exist.         |
| Natural farming eliminates the need for external nutrients. | Continuous cropping removes nutrients from soil. Long-term sustainability may still require balanced nutrient management.                                      |
| Natural farming reduces farmer income.                      | Many reports show improved net income mainly due to reduced input costs, not necessarily higher yields. Profitability depends on local conditions and markets. |
| Natural farming alone can solve                             | Agrarian distress is multi-dimensional (market, climate,                                                                                                       |

|                  |                                                                                                  |
|------------------|--------------------------------------------------------------------------------------------------|
| agrarian crisis. | policy issues). Natural farming can help reduce costs but is not a complete standalone solution. |
|------------------|--------------------------------------------------------------------------------------------------|

The future of Indian agriculture lies in the transition from an **"input-heavy"** industrial model to a **"knowledge-heavy"** biological model. Natural Farming is not a return to primitive methods but a sophisticated application of natural laws to modern food production. As the Green Revolution's limitations become increasingly apparent through soil death and economic distress, the SPNF model provides a scientifically backed, socially equitable, and ecologically sound path forward for the farming community. By harnessing the microbial potential of the Desi cow and the structural benefits of mulching, farmers can achieve the dual goals of economic prosperity and environmental stewardship.

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# Emerging Rice Diseases in the Era of Climate Change

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## 1. Rice False Smut

### Introduction

Rice false smut, caused by *Ustilaginoidea virens* (Cooke) Takahashi, has emerged as one of the most important diseases of rice in recent decades. Once regarded as a minor disease occurring sporadically, it has now become a major concern in many rice-growing regions due to the widespread cultivation of high-yielding and hybrid varieties, excessive nitrogen fertilization, and favorable environmental conditions. Besides reducing grain yield and quality, the disease contaminates harvested grain with fungal toxins, posing concerns for food safety and seed quality.



### Symptoms

False smut symptoms appear only after flowering, during the grain-filling stage. Instead of developing into healthy grains, individual spikelets are transformed into velvety smut balls. Initially, these smut balls are yellowish-orange, gradually enlarging and turning olive green to dark green, and finally becoming black as the fungus matures. The smut balls are usually larger than normal grains and

are covered with a powdery mass of spores. Infected panicles often contain only a few smutted grains, while the remaining grains may appear normal. Under severe infection, grain filling is reduced, resulting in poor grain quality and lower market value.

### Distribution and Occurrence

Rice false smut is now reported from almost all major rice-growing countries, including India, China, Japan, Bangladesh, Vietnam, Thailand, the Philippines, South Korea, the United States, and several African countries. In India, the disease has become increasingly common in major rice-producing states such as Punjab, Haryana, Uttar Pradesh, Bihar, West Bengal, Odisha, Chhattisgarh, Madhya Pradesh, Telangana, Andhra Pradesh, Tamil Nadu, Karnataka, Assam, and Maharashtra. The disease is particularly severe in regions experiencing high humidity (above 90%), frequent rainfall, temperatures of 25–30°C during flowering, dense crop canopy, and excessive nitrogen application.

### Importance from a Plant Pathology Perspective

From a plant pathology standpoint, rice false smut presents several significant challenges:

- Emerging disease status: The disease has increased dramatically over the last two decades, making it an important emerging disease in rice ecosystems.
- Difficult diagnosis: Infection occurs before visible symptoms appear, making early detection difficult in the field.



- **Complex infection biology:** The pathogen infects floral organs during booting and flowering, and its infection process is not yet fully understood.
  - **Toxin production:** The fungus produces ustiloxins and ustilaginoidins, secondary metabolites that are toxic to plants and may contaminate harvested grains.
  - **Limited resistant varieties:** Most commercial rice cultivars are susceptible or only moderately resistant, limiting the effectiveness of host resistance.
  - **Influence of climate change:** Warmer temperatures, increased humidity, and altered rainfall patterns are creating conditions favorable for disease development and wider geographical spread.
  - **Seed health concerns:** Smut balls contaminate seed lots, reducing seed quality and creating challenges in seed certification and trade.
  - **Integrated disease management challenges:** Effective control requires a combination of resistant cultivars, balanced nutrient management, timely fungicide application, clean seed, and disease forecasting, yet reliable forecasting systems remain limited.
- **Assessing the impact of climate change on disease epidemiology.**
- Rice false smut has evolved from a minor disease into a major constraint to sustainable rice production. Continued research, improved surveillance, resistant varieties, and integrated disease management strategies are essential to reduce its impact on rice productivity and grain quality.

## 2. Rice Bacterial Panicle Blight

### Introduction

Rice bacterial panicle blight (BPB), caused primarily by *Burkholderia glumae* and occasionally by *Burkholderia gladioli*, is an emerging bacterial disease that affects rice during the reproductive stage. The disease has gained importance worldwide due to rising temperatures, increased humidity, and changes in rice cultivation practices. Bacterial panicle blight causes poor grain filling, spikelet sterility, and significant yield losses, making it a growing concern under climate change. Although traditionally reported in tropical and subtropical regions, its distribution has expanded into temperate rice-growing areas.



### Symptoms

Symptoms usually appear from the booting to grain-filling stage. Infected panicles show partial or complete sterility, with florets becoming brown to dark brown. Spikelets often fail to fill properly,

### Research Needs

- Understanding pathogen diversity and evolution.
- Identifying durable sources of host resistance.
- Developing rapid molecular diagnostic tools.
- Studying host–pathogen interactions at the molecular level.
- Establishing weather-based disease forecasting models.
- Evaluating biological control agents and environmentally friendly management practices.



resulting in empty or partially filled grains. Affected panicles remain upright because of the low grain weight. Brown discoloration is commonly observed on the glumes, and under severe infection, the entire panicle may become blighted. Seedlings produced from infected seeds may exhibit poor germination and weak growth, while infected seeds often show reduced vigor and quality.

### Distribution and Occurrence

Rice bacterial panicle blight has been reported from Japan, South Korea, China, Taiwan, the Philippines, Thailand, Vietnam, Malaysia, Indonesia, the United States, Brazil, Colombia, and several other rice-producing countries. In India, reports are comparatively limited but increasing, with the disease detected in states such as Punjab, Haryana, Uttar Pradesh, Telangana, Andhra Pradesh, Tamil Nadu, Karnataka, Odisha, and Chhattisgarh. The disease is favored by high temperatures (30–35°C), high relative humidity, frequent rainfall, and warm nights during flowering, conditions that are becoming more common due to climate change.

### Importance from a Plant Pathology Perspective

- **Emerging disease:** The disease is becoming more frequent and severe in many rice-growing regions as climatic conditions become more favorable.
- **Seed-borne nature:** *Burkholderia glumae* can survive on infected seeds, facilitating long-distance dissemination and making seed health management essential.
- **Difficult diagnosis:** Early symptoms resemble heat stress, grain sterility, or other panicle disorders, often leading to misdiagnosis in the field.
- **Limited resistant varieties:** Most cultivated rice varieties possess little or no effective resistance, limiting host-based disease management.
- **Rapid disease development:** The pathogen multiplies rapidly under warm and humid

conditions, causing sudden disease outbreaks during flowering.

- **Climate change sensitivity:** Elevated temperatures significantly enhance disease severity, making bacterial panicle blight a climate-sensitive disease.
- **Complex pathogen biology:** The bacterium produces virulence factors, including toxoflavin, which damages host tissues and contributes to severe grain sterility.
- **Limited management options:** Chemical control is often inconsistent because infection occurs during flowering, and effective bactericides are limited. Integrated management strategies are therefore essential.

### Research Needs

- Identification of resistant rice germplasm and resistance genes.
- Development of rapid molecular diagnostic techniques for early detection.
- Studies on pathogen diversity, virulence mechanisms, and population genetics.
- Improved understanding of host–pathogen interactions and toxin production.
- Development of weather-based forecasting and early warning systems.
- Evaluation of biological control agents and eco-friendly disease management practices.
- Assessment of the impact of climate change on disease epidemiology and geographic distribution.

Rice bacterial panicle blight is an emerging bacterial disease that poses a serious threat to rice productivity, grain quality, and seed health. Increasing temperatures and humidity associated with climate change are expected to enhance its spread and severity. Strengthening disease



surveillance, improving seed health standards, developing resistant cultivars, and implementing integrated disease management strategies are essential to minimize its impact and ensure sustainable rice production.

### 3. Rice Bakanae Disease

#### Introduction

Rice bakanae disease, caused primarily by *Fusarium fujikuroi*, is one of the oldest known diseases of rice and has recently re-emerged as a significant threat in many rice-growing countries. The disease has become increasingly important due to the widespread use of infected seed, intensive rice cultivation, climate change, and the development of fungicide-resistant pathogen populations. Bakanae, meaning "foolish seedling" in Japanese, is characterized by abnormal elongation of infected seedlings caused by the production of gibberellins by the pathogen. Severe outbreaks can result in poor crop establishment, reduced plant population, and substantial yield losses.



#### Symptoms

Symptoms may appear from the nursery stage to crop maturity. The most characteristic symptom is abnormal elongation of infected seedlings, which become tall, thin, pale green or yellowish, and weak compared to healthy plants. Infected seedlings often show elongated internodes, reduced root

development, and poor tillering. As the disease progresses, affected plants become stunted or wilt, eventually drying and dying before or after transplanting. In some cases, plants survive until maturity but produce partially filled or empty panicles with poor grain quality. White to pink fungal growth may be observed at the stem base under humid conditions, and infected grains often serve as the primary source of inoculum.

#### Distribution and Occurrence

Rice bakanae disease is widely distributed across Asia, Europe, Africa, North America, and South America. It has been reported from major rice-producing countries including Japan, China, South Korea, India, Bangladesh, Pakistan, Vietnam, Thailand, the Philippines, Italy, Spain, and the United States. In India, the disease has become increasingly prevalent in Punjab, Haryana, Uttar Pradesh, Uttarakhand, Bihar, West Bengal, Odisha, Chhattisgarh, Madhya Pradesh, Telangana, Andhra Pradesh, Tamil Nadu, Karnataka, Assam, and Maharashtra. Disease development is favored by warm temperatures (25–35°C), high humidity, infected seed, continuous rice cultivation, and poor seed treatment practices.

#### Importance from a Plant Pathology Perspective

- Re-emerging disease: Once considered a manageable disease, bakanae has re-emerged due to increased reliance on seed-borne inoculum and changing environmental conditions.
- Seed-borne transmission: The pathogen survives within and on rice seeds, making infected seed the primary source of disease spread across regions and countries.
- Difficult early diagnosis: Initial symptoms may resemble nutrient deficiency, hormonal imbalance, or other seedling disorders, making field diagnosis challenging.





- Fungicide resistance: Populations of *Fusarium fujikuroi* resistant to commonly used seed-treatment fungicides have been reported, reducing the effectiveness of conventional management.
- Complex pathogen diversity: The *Fusarium fujikuroi* species complex exhibits considerable genetic variability, complicating disease diagnosis and resistance breeding.
- Climate change influence: Rising temperatures and changing rainfall patterns favor pathogen survival, infection, and disease development, increasing the risk of epidemics.
- Yield and seed quality losses: Infection reduces plant stand, tillering, grain filling, and seed quality, affecting both productivity and seed certification programs.
- Need for integrated management: Sustainable control requires disease-free certified seed, effective seed treatment, resistant cultivars, biological control, and regular field monitoring.



### Research Needs

- Identification of durable genetic resistance against *Fusarium fujikuroi*.
- Development of rapid molecular and field-based diagnostic tools for seed testing.
- Monitoring fungicide resistance and identifying alternative seed treatment options.
- Understanding pathogen diversity, epidemiology, and host-pathogen interactions.
- Development of biological control agents and environmentally safe disease management strategies.

- Evaluation of climate change impacts on disease occurrence and geographic distribution.
- Integration of disease forecasting with seed health surveillance programs.

Rice bakanae disease has re-emerged as a major seed-borne disease threatening sustainable rice production worldwide. The increasing use of infected seed, evolution of fungicide-resistant pathogen populations, and favorable climatic conditions have contributed to its growing importance. Effective management will depend on the use of healthy certified seed, improved diagnostic techniques, resistant varieties, integrated disease management, and continued research on pathogen biology and climate-resilient disease control strategies.

### 4. Rice Blast: Emerging Pathotypes

#### Introduction

Rice blast, caused by *Magnaporthe oryzae*, is the most destructive fungal disease of rice and is responsible for significant yield losses worldwide. Although the disease has been known for centuries, the continual emergence of new virulent pathotypes (races) has made rice blast an evolving threat to sustainable rice production. These new pathotypes can overcome the resistance genes present in widely cultivated rice varieties, leading to frequent disease outbreaks. Climate change, intensive monoculture, widespread cultivation of genetically similar varieties, and fungicide selection pressure have accelerated the evolution and spread of new blast pathotypes, making disease management increasingly challenging.

#### Symptoms

- Leaf blast: Diamond-shaped or spindle-shaped lesions with gray or whitish centers and dark brown margins appear on leaves. Under severe infection, lesions coalesce, causing extensive leaf drying.





- Collar blast: Infection occurs at the junction of the leaf blade and sheath, resulting in drying and death of affected leaves.
- Node blast: Infected nodes become dark brown or black, weakening the stem and increasing the risk of lodging.
- Neck blast: The neck of the panicle turns brown or black, leading to incomplete grain filling, panicle breakage, or complete sterility. Neck blast is the most damaging phase of the disease because it directly reduces grain yield.



### Distribution and Occurrence

Rice blast occurs in more than 85 rice-growing countries and is prevalent in Asia, Africa, Europe, North America, South America, and Australia. In India, the disease is widespread in Madhya Pradesh, Chhattisgarh, Odisha, West Bengal, Assam, Bihar, Jharkhand, Uttar Pradesh, Uttarakhand, Punjab, Haryana, Telangana, Andhra Pradesh, Karnataka, Tamil Nadu, Kerala, Maharashtra, and the North-Eastern states. Disease development is favored by temperatures of 24–28°C, relative humidity above 90%, prolonged leaf wetness, frequent rainfall, cloudy weather, excessive nitrogen fertilization, and dense crop canopy.

### Importance from a Plant Pathology Perspective

- Rapid evolution of pathogen races: *Magnaporthe oryzae* has a highly variable genome and evolves quickly through mutation, recombination, and genetic exchange, leading to the continual emergence of new virulent pathotypes.
- Breakdown of host resistance: Newly evolved pathotypes frequently overcome major blast resistance (R) genes, reducing the durability of resistant rice cultivars.
- Wide host adaptation: The pathogen infects numerous rice genotypes and can rapidly adapt to new host backgrounds.
- Climate change influence: Increased temperature fluctuations, high humidity, and irregular rainfall create favorable conditions for disease development and accelerate pathogen evolution.
- Fungicide resistance: Repeated use of site-specific fungicides, particularly strobilurins and triazoles, has led to reduced sensitivity in some pathogen populations, complicating disease management.
- High genetic diversity: Considerable variation exists among pathogen populations across different agro-climatic regions, making resistance breeding more difficult.
- Threat to food security: Severe epidemics can cause 30–70% yield loss, while under highly favorable conditions, losses may exceed 80%, particularly when neck blast develops during the reproductive stage.
- Need for continuous surveillance: Monitoring pathogen races and virulence patterns is essential to guide breeding programs and develop durable resistance.

### Research Needs



- Identification and monitoring of emerging blast pathotypes using molecular and genomic tools.
  - Discovery and pyramiding of durable blast resistance genes (R genes and quantitative resistance loci).
  - Understanding pathogen population structure and evolution under changing climates.
  - Development of rapid molecular diagnostics and field-based detection systems.
  - Use of artificial intelligence, remote sensing, and precision agriculture for early disease detection.
  - Identification of novel fungicides and biological control agents to manage fungicide-resistant populations.
  - Development of weather-based disease forecasting and decision-support systems for timely management.
- Rice blast remains the most economically important disease of rice because of the continual emergence of new virulent pathotypes capable of overcoming host resistance. Climate change, intensive rice cultivation, and pathogen evolution have transformed blast into a dynamic and persistent threat. Sustainable management requires continuous pathogen surveillance, deployment of durable resistant varieties, integrated disease management, and advanced genomic and digital technologies to reduce the impact of this devastating disease on global rice production.
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# Revitalization of Ravine Landscapes Using Karanj (*Pongamia pinnata*)

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## Introduction

Energy is an essential unit for economic development of any nation. The energy besides alleviating poverty also helps to improve the quality of life for rural people. The demand for energy in particular the diesel energy augmenting across the country due to increase the number of vehicles in transport sector. The transport and industrial sector consume millions of tons of diesel energy every year which results in depletion of fossil fuel resources and also increased pollution hazards. This necessitated searching for alternate and renewable energy resources which are productive and also provide clean environment. In this context, forest of the country which are housed with more than hundred different species which could yield oil utilizable for edible purpose and also for non-edible purpose. Among the hundreds species the potential of karanj as a source of energy resource has been well establish and documented. Biofuel has also been more attractive recently because it is renewable, socio economically viable and environmentally beneficial. Biofuel is an environmentally beneficial alternative to diesel fuel made from domestic renewable resources, such as animal fats and vegetable oils (edible or non-edible). There are hundreds of species in India that potentially provide oilseeds with sufficient potential to be used in the manufacturing of biodiesel. Due to India's lack of edible oils, non-edible oils may be the preferred source for the manufacturing of biodiesel (Vennila *et al.*, 2022). The karanj tree which is indigenous to India and can grow wide range of edapho-climatic condition and thus, found as one of the alternate resource for biodiesel production.

## Present status Karanj in India

*Pongamia pinnata* is widely distributed across India in tropical, subtropical and dry regions from coastal Kerala and Odisha, entire semi-arid parts of Rajasthan and inland central India. It occurs naturally and as planted specimens across various habitats, including tropical dry and moist deciduous forests and urban landscapes. The demands for petrol and diesel are rapidly increasing in developing countries. In India, the rate of growth is extremely high (Katwal and Soni, 2003). According to Gyanaranjan Sahoo *et al.* (2020), the consumption rose from 37 million metric tonnes in 1970 to 222.79 million metric tonnes in 2020–2021. In order to meet its energy needs, the nation imports over 78% of its crude oil and makes significant foreign exchange investments. Over the past few years, crude oil prices have skyrocketed on the global market. However, the overuse of fossil fuels is changing the global climate by releasing a significant amount of greenhouse gases (GHGs) into the atmosphere.

Growing concern over increasing prices of fossil fuels, depleting oil reserves coupled with environmental degradation has prompted to search alternative, renewable, economically viable and environmentally safe fuels derived from plant origin usually termed as biofuels (Kesari *et al.* 2009). India places a strong emphasis on utilizing karanj oil's potential as a source of biodiesel because to its low viscosity, superior fuel qualities, and ability to safely blend up to 20% of it with biodiesel without requiring any modifications to current diesel engines (Shrinivasa, 2001). Karanj oil has shown to be a great feedstock for the nation's manufacture of biodiesel.



In accordance with the Kyoto Protocol, the Indian Planning Commission has decided to blend 5–10% biodiesel starting in 2010 in order to comply with Euro III standards.

Karanj seed oil as a bio- fuel has physical properties very similar to conventional diesel. Emission properties, however, are cleaner for Bio-fuel than for conventional diesel. It has no polyaromatic compounds and reduced toxic smoke and soot emissions. A drastic reduction in sulphur content (<350ppm) and higher cetane number (>51) will be required in the petroleum diesel produced by refineries. However, bio-fuel meets these two important specifications and would help in improving the lubricity of low sulphur in (0.13-0.16%) diesel. The present specification of flash point for petroleum diesel is 350 °C which is lower than some other countries in the world (>550°C). Bio-fuel will help in raising the flash point, a requirement of safety.

### **Why we prefer Karanj tree species under non-arable landscapes?**

The tree is well suited to intense heat and sunlight and its dense network of lateral roots and its thick, long taproot make it drought tolerant. The dense shade it provides slows the evaporation of surface water and its root structures promote nitrogen fixation, which moves nutrients from the air into the soil. Karanj is a highly suitable species fast growing for ravine and degraded land afforestation in order control soil erosion and quickly cover land biomass production. Plantation of Karanj is advantageous since it is a leguminous tree, possesses tolerance to saline and alkaline soils and exhibits capacity for higher yields. Karanj is another oil seed tree, which can provide you a higher yield per ha, but one can expect the yield only after 4 to 6 years through clone plantation. Ultimately, plantation of Karanj is advantageous since it is a leguminous tree, possesses tolerance to saline and alkaline soils and exhibits capacity for higher yields.

### **Potential of Karanj**

The tree is well suited to intense heat and sunlight and its dense network of lateral roots and its thick, long taproot make it drought-tolerant. The dense shade it provides slows the evaporation of surface water and its root nodules promote nitrogen fixation, a symbiotic process by which gaseous nitrogen (N<sub>2</sub>) from the air is converted into ammonium (NH<sub>4</sub><sup>+</sup>, a form of nitrogen available to the plant). Withstanding temperatures slightly below 0 °C (32 °F) and up to about 50 °C (120 °F) and annual rainfall of 500–2,500 mm (20–100 in), the tree grows wild on sandy and rocky soils, including oolitic limestone, but will grow in most soil types, even with its roots in salt water. More specifically *P. pinnata* is an outbreeding diploid legume tree, with a haploid chromosome number of 11. Root nodules are of the determinate type (as those on soybean and common bean) formed by the causative bacterium *Bradyrhizobium*.

Since the beginning of time, plants have been utilized extensively as remedies for a wide range of illnesses. Today's market offers a wide range of herbal treatments that contain concentrated fruit or seed extract. Natural health practitioners use Karanj prepared oil, which is widely accessible, to treat rheumatism. The oil has been treated as fuel in diesel engine showing good thermal efficiency. Oil is also used as a fuel for cooking and burning of lamps, as a lubricant, water paint binder, pesticides and tanning industries. Karanja is a fast-growing semi-deciduous tree which reaches 40 feet in height and spread, forming a broad, spreading canopy casting moderate shade. The tree after 7 - 8 years reaches full productivity of about 6 – 9 tonnes of seeds / ha / year. These beautiful blossoms and the glossy, nearly-evergreen leaves help make Karanj a favorite for use as a specimen, shade, or windbreak.

### **Distribution and Ecology**

*Pongamia pinnata* is a species of tree in the pea family- Fabaceae that is native to southern Asia.



Common names include Karanj, Indian Beech Tree, Honge Tree, Pongam Tree, *Honge* (Kannada), *Pungai* (Tamil), and *Naktamāla* (Sanskrit). An Indo-Malaysian species, a medium-sized sub-evergreen tree, common on alluvial and coastal situations from India to Fiji, from sea level to 1200 m. Now it is found in Australia, Florida, Hawaii, India, Malaysia, Oceania, Philippines, and Seychelles. Karanj grows throughout the greater parts of the country chiefly along streams and rivers and in beach and tidal forests. It is considered to be a native of the Western Ghats. Ranges from Tropical Dry to Moist through Subtropical Dry to Moist Forest Life Zones. Native to humid and subtropical environments, Karanj thrives in areas having an annual rainfall ranging from 500 to 2500 mm in its natural habitat, the maximum temperature ranges from 27 to 38°C and the minimum 1 to 16°C. Mature trees can withstand water logging and slight frost. This species grows to elevations of 1200 m, but in the Himalayan foothills is not found above 600 m.

### Physiognomy

*P. pinnata* is a deciduous legume tree that grows to about 15–25 meters (15–80 ft) in height with a large canopy which spreads equally wide. The leaves are a soft, shiny burgundy in early summer and mature to a glossy, deep green as the season progresses. Flowering starts in general after 3–4 years in the month of April to June. The pods ripen March to May of the following year, single almond sized seeds can occur by 4–6 years. Small clusters of white, purple, and pink flowers blossom on their branches throughout the year, maturing into brown seed pods. Pods are 4.5 cm long & 1.5-2.5 cm wide broad, pointed at both ends, yellowish grey when ripe, 1 or 2 seeded. Seeds are elliptical, reniform, compressed, reddish brown, fairly hard, 2-3 cm long. The pods ripen from February to May in the following year. The bark of Karanj is smooth, grey and thin.

*P. pinata* has been subjected to chemical investigations extensively and several chemical

constituents belonging to the different groups, viz. alkaloids, tannins, glycosides, steroids, saponins, flavonoids have been reported. The plant mainly contains alkaloids, protein, fatty oil, tannins, and a mixture of fatty acids (Bholane and Hiremath, 2020). Karanj grows in wide range of edapho-climatic condition ranging from stony to sandy to clayey. It does not do well on dry sands. It is highly tolerant of salinity. It is common along waterways or seashores, with its roots in fresh or salt water. Highest growth rates are observed on well drained alluvial soils with assured soil moisture.

### Silvicultural characters and Reproduction

Karanj is a shade bearer and can grow under the shade of other trees. It is, however, not a shade demander and grows well with overhead light. The seedlings stand frost fairly well; the leaves, which may be affected by frost, drop off and the streams remain unaffected. The tree is drought resistant and is well adapted to adverse soil and moisture conditions. Prolonged drought may, however, kill the seedlings. It pollards well and produces root suckers readily. It is an excellent coppice. It produces through seed, root suckers and coppice. Natural regeneration from seed is usually plentiful under forest conditions. Karanj can be raised by direct sowing or by planting out of entire plants or stumps; the latter two methods give equally good results. Branch cuttings can also be used for raising this species.

### Cultivation strategies:

#### Nursery Practices

##### a. Seed Collection and Storage

The pods are to be collected from the identified plus trees during April to December. They are dried in sun and seeds are extracted by thrashing the fruits. Seeds can be stored for a period of 6 months and they retain their viability for one year when stored at 5°C. The seeds should not be extracted





and must be stored with the pod unopened in sealed polythene bags.

### b. Seed germination

Seeds are sown in sand trays with the micropyle facing downwards. Seeds start germinating from 10<sup>th</sup> day of sowing. Treating the seeds by soaking in hot water for 15 minutes improves germination percent and also vigour. Treat the seeds in a fungicidal solution before sowing help to prevent fungal diseases in the nursery.

### c. Seedling origin

Seedlings are raised in seed beds or polybags. The seeds are dibbled in the nursery beds in the beginning of hot weather, at a spacing of 7.5 cm x 1.5 cm. Germination of seeds will be completed in about 20 - 30 days and more than 80 per cent germination can be achieved from good quality, well stored healthy seeds. The germinated seedlings at two leaf stages are then pricked out and transplanted to polybags (Photo.1).

### c. Vegetative Propagation

Karanj, being a hardwood species can be propagated through hardwood cuttings. It can be propagated by treating semi-hardwood cuttings with IBA under low cost mist conditions. It gives 76.67% of rooting success. Suitable period for grafting to obtain maximum success of grafts were reported at August (53.90%), September (51.75%) and October (50.98%) by Kala *et al.*, (2022). Above three months having optimum temperature and humidity which favours higher rate of success in epicotyl grafting and it is considered as a most suitable period for the propagation of Karanj. Kala *et al.*, (2018) Present study investigated the effects of IBA on rooting of stem cuttings in this species. Percentage rooting and primary root number differed significantly between treated and untreated cuttings. Treatment of cuttings with 3000 ppm IBA maximized rooting (89.0%), along with increased survival (84.0%) and primary

root number (18.7). Rooting success and root number were better in 15 cm x 25 mm diameter sized cuttings. Cuttings planted in sand: soil: VAM (2:1:1) rooted better, with more roots ensuring better survival. Survival and growth of the clonal plants were best when using improved and easy techniques like size of the cuttings with proper concentration IBA and also combined with suitable rooting media. Grafting viz., cleft grafting method has also been developed to mass multiply superior genetic resource. Through grafting more than 80% success can be achieved (Photo.1).



Photo- 1. Seed based quality Seedling Production in Karanj



Photo- 2. Vegetative propagation of *Pongamia pinnata* (Karanj) through stem Cutting

### Establishment

Six months old quality seedlings / clonal plants from stem cutting of superior mother trees are selected for planting out. For establishing field trials,



biodiesel and energy plantations, 5 x 5 m spacing is adopted to facilitate better branch development and enable cultural operations. The seedlings are planted in square pits of 30 - 45 cm<sup>3</sup> during the rainy season. Intercropping may also be done during the initial years of establishment.

### **Agroforestry practices- Karanj based silvipasture system ideal for non-arable ravine lands**

Agroforestry plays an important role in the economy of arid and semi-arid regions due to high risk involved with arable farming, which is affected by low and highly variable rainfall, low soil fertility and high wind velocity. Karanj growth was improved through Half-moon micro catchment based moisture conservation techniques in silvipasture system as compared to sole plantation. It is evident from the results that the cost of establishment of plantation can be met out through intercropping during the gestation period of Karanj intercropping, especially during the tree gestation period, could be economically profitable and is environmentally sound indeed, given the prevalent hostile environmental conditions in arid and semi-arid regions (Kala et al., 2019). Recently, India has announced the National Agroforestry Policy, 2014, advocating the growing of trees on farms to meet a wide range of products such as fodder, fuel and timber. Karanj based silvipasture system developed with spacing at 5m x 5 m spacing with fodder grasses of *Dichanthium annulatum* (marvel grass) which is highly successful in Chambal ravine land rehabilitation. Karanj based silvipasture system gives many direct income /benefits and supplemental green fodder grass yield as an additional income (Kala et al., 2020). The B: C ratio of the system is 1.32. It indicates that this technology is economically viable and ecologically suitable for ravine lands. Play significant role in Biomass Carbonstock, SOC and carbon sequestration service under ravine ecosystem as an ecosystem or intangible benefits.



Photo-3. Karanj based silvipasture system ideal for non-arable ravine lands

### **Harvesting, Yields and Economics**

The tree starts bearing at the age of 6 – 8 years. The parts come to harvest at the different periods of the year in different parts of the country but the harvest session extends from June to December. The seed yield per tree ranges between 10 kgs (10 years) and 200 kgs (50 years and above). Trees reach adult height in 4 or 5 years, bearing at the age of 4–7 years. A single tree is said to yield 9–90 kg seed per tree, indicating a yield potential of 900-9000 kg seed/ha from well managed plantation (yield variation depends upon age, growth and site condition), Genotypes or Seed sources with more than 30% oil content are identified by Indian Institutes. Genetic improvement, propagation techniques, and germplasm evaluation are important research areas, with more than a thousand accessions collected for study. Hence, seed oil content of selected trees is more than 40%, which should help increase Karanj oil production and reduce the cost of the biofuel derived from the oil.

### **Benefits of *Pongamia pinnata* (Karanj) for Rehabilitation of Degraded Lands**

The Karanj tree is well-adapted to semi-arid regions and degraded landscapes and it has many traditional uses.



- **Improves Soil Fertility** – Fixes atmospheric nitrogen, enriching poor soils.
- **Tolerates Harsh Conditions** – Thrives in saline, drought-prone, and marginal lands.
- **Enhances Soil Organic Matter** – Leaf litter and seed cake improve soil structure.
- **Supports Biodiversity** – Provides habitat and shade for other plant and animal species.
- **Soil and water conservation:** Karanj is a highly suitable species; deep root system stabilizes loose and degraded soils to prevent soil erosion. Due to fast growing nature, highly suitable for ravine and degraded land afforestation in order control soil erosion and quickly cover land biomass production.
- **Carbon Sequestration** – Absorbs CO<sub>2</sub>, aiding climate change mitigation.
- **Low Maintenance** – Requires minimal inputs once established.
- **Economic Value and Aesthetic use**– Produces oil-rich seeds useful for biodiesel and rural income generation. It is often used for landscaping purposes as a windbreak or for shade due to the large canopy and showy fragrant flowers.

## Conclusion

Karanj (*Pongamia pinnta*) is a highly valuable tree in oilseed production, biopesticide purpose in organic farming agriculture, tree medicine, and environmental conservation. It is native to South and Southeast Asia and is widely grown in countries like India, Sri Lanka, and parts of Australia. Karanj is a leguminous plant that improves soil fertility by fixing atmospheric nitrogen. Indians living in rural areas are familiar with this species because its oil has traditionally been used to light household lamps. It grows well throughout most of the nation. One of this species' special features is its

ability to withstand extreme drought and waterlogging. In arid areas, it is one of the few species that remains green all summer long. This species' ability to fix nitrogen from the atmosphere is an additional advantage. According to traditional medical systems like Ayurveda and Unani, the Karanj plant contains anti-inflammatory, anti-plasmodial, anti-noniceptive, anti-hyperglycemic, anti-lipid peroxidative, anti-diarrheal, anti-ulcer, anti-hyperammonic, and antioxidant qualities. Its deep root system prevents soil erosion. It can grow in poor, saline, and dry soils. Helps reduce atmospheric carbon dioxide. Karanj is an eco-friendly, hardy-multipurpose tree, it plays a major role in improving soil health, producing renewable energy, supporting traditional medicine, and promoting sustainable agriculture. Hence, Karanj is an ideal for converting non-arable, deep gullies into pastures and fodder banks to protect them from overgrazing while providing livelihood resources. Biodiesel has emerged as one of the promising options and production of its raw material, oilseeds, is now gaining importance and matter of great concern is meeting the energy needs of the rapidly growing economy of the country. Efforts to identify elite genotypes and standardize growth practices are still in their early stages for this species. Among the many favourable attributes of agroforestry is its suitability for degraded land. It is an alternative available for the rehabilitation and utilization of the vast expanse of ravine kind of degraded wastelands in the country. The use of ravine lands to produce Karanj oilseeds can realize the twin objectives of rehabilitation of a vital land resource and obtaining an energy substitute. Hence, Karanj based green revival of ravine landscapes involves transforming severely eroded "badlands" into productive, stable ecosystems through a combination of engineering, agroforestry, and community-led initiatives in restoring degraded ecosystems sustainably.





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## Keelara Village's Community-Owned Organic Store: A Grassroots Model for Rebuilding Local Food Systems

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Across rural India, villages are searching for ways to make farming more profitable, protect natural resources, and ensure that healthy food reaches local communities. In Karnataka's Mandya district, the village of Keelara has responded to these challenges through an innovative, community-driven solution. Rather than sending all its produce to distant markets, the village has established a community-owned organic produce store, where local residents receive first access to organically grown fruits and vegetables, while only the surplus is marketed to urban consumers.

Keelara is located in Mandya Taluk of Mandya District, Karnataka, approximately 12 km from Mandya city and about 96 km southwest of Bengaluru along National Highway 275. The village covers a geographical area of 739.04 hectares (7.39 km<sup>2</sup>) and had a population of 5,112 people living in 1,210 households, according to the 2011 Census. Situated at an elevation of around 690–700 metres above sea level, the village lies within the fertile Cauvery River basin, benefiting from an extensive canal irrigation network that supports year-round cultivation. Agriculture is the primary occupation, with major crops including paddy, sugarcane, ragi (finger millet), fruits, and vegetables.

The initiative, developed with the support of the Mandya Organic Farmers Cooperative, represents far more than a retail outlet. It reflects a new approach to rural development that places farmers, consumers, and the local economy at the centre of the food system. By encouraging organic cultivation, reducing dependence on long supply chains, and ensuring that locally produced food is first made available to

village residents, Keelara has created a model that strengthens food security while improving farmers' livelihoods. Only the surplus produce is transported to Organic Mandya outlets in nearby urban centres, enabling farmers to access larger markets without compromising local food availability.

Keelara was selected as a study area because it represents one of Karnataka's pioneering examples of a community-owned organic food distribution model. The village possesses several characteristics that make it an ideal case study. Its fertile irrigated agricultural land provides favourable conditions for diversified organic farming; its proximity to Mandya town enables efficient marketing of surplus produce; and the active participation of farmers through the Mandya Organic Farmers Cooperative has facilitated collective decision-making and community ownership. The village demonstrates how local institutions can successfully integrate sustainable agricultural practices with cooperative marketing, thereby enhancing economic resilience and strengthening rural livelihoods.

At a time when concerns over food safety, climate change, biodiversity conservation, and declining farm incomes are influencing agricultural policies worldwide, Keelara offers a practical example of how rural communities can build food systems that are economically viable, environmentally sustainable, and socially inclusive. By prioritizing local consumption, promoting organic farming, reducing food transportation, and empowering farmers through cooperative action, the village illustrates an effective pathway toward sustainable rural





development and serves as a valuable model for replication in other agricultural regions.

### **Reversing the Conventional Food Supply Chain: Keelara's Local-First Food System**

For much of India's agricultural history, the movement of food from farms to consumers has been organised around large wholesale markets. Farmers harvest their produce and transport it to Agricultural Produce Market Committees (APMCs), where licensed traders and commission agents purchase crops through auction or negotiated sales. The produce then passes through a chain of wholesalers, distributors, transport companies, retailers, and street vendors before finally reaching consumers. This conventional supply chain has enabled agricultural commodities to reach large urban markets, but it has also become increasingly complex, involving multiple stages of handling, transportation, storage, and commercial transactions. Each additional intermediary contributes to higher marketing costs, longer travel distances, greater post-harvest losses, and lower returns for producers.

One of the paradoxes of this system is that vegetables grown in rural villages often travel hundreds of kilometres before returning to consumers who live only a short distance from the farms where they were produced. For instance, vegetables harvested in Mandya district may first be transported to wholesale markets in Bengaluru or Mysuru, where they are graded, auctioned, repacked, and redistributed through retail supply chains. Ironically, some of these same vegetables eventually find their way back to nearby villages through local retailers. Such circular movement increases transportation costs, fuel consumption, labour expenses, and packaging requirements while generating unnecessary greenhouse gas emissions. At every stage, additional handling increases the likelihood of physical damage, spoilage, moisture loss, and deterioration in nutritional quality.

The Food and Agriculture Organization (FAO) estimates that approximately 13% of food produced globally is lost between harvest and retail, while significant additional quantities are wasted at the consumer level. Fruits and vegetables are among the most vulnerable commodities because they are highly perishable and sensitive to temperature, humidity, and mechanical damage during transport. These losses not only reduce farmers' incomes but also represent wasted water, land, energy, labour, and agricultural inputs invested in producing the food. Consequently, reducing post-harvest losses has become a major global priority for improving food security and environmental sustainability.

Keelara village has deliberately challenged this conventional model by reorganising the movement of agricultural produce around the needs of its own community. Instead of viewing distant wholesale markets as the default destination for every harvest, the village has adopted a local-first food distribution system. Farmers bring their organically grown vegetables, fruits, leafy greens, pulses, spices, and other farm products directly to the village-owned organic produce store immediately after harvest. This community-managed outlet functions as the first point of sale, allowing local households to purchase fresh food produced within their own village.

This reversal of the traditional supply chain represents a fundamental shift in agricultural marketing priorities. Rather than exporting the entire harvest and relying on external markets to determine food distribution, Keelara first satisfies local nutritional needs. Only after village demand has been fully met is the remaining surplus transported to Organic Mandya retail outlets that serve consumers in Bengaluru, Mysuru, Mandya, and neighbouring urban centres. External markets therefore become destinations for surplus production instead of the primary focus of agricultural marketing.

The benefits of this approach extend far beyond reducing transportation distances. By keeping food



within the village whenever possible, farmers are able to market freshly harvested produce with minimal delay. Vegetables often reach consumers within hours of harvest, preserving freshness, flavour, texture, and nutritional quality. Because produce undergoes fewer loading and unloading operations, physical damage and spoilage are substantially reduced. Lower transportation requirements also decrease the need for extensive packaging materials, thereby reducing plastic waste and associated environmental impacts.

Economically, the shortened supply chain enables farmers to capture a greater share of the final consumer price. In conventional markets, numerous intermediaries each add margins that increase retail prices while reducing the proportion of revenue reaching producers. Keelara's village-owned store eliminates many of these intermediary stages, allowing consumers to purchase organic produce at competitive prices while ensuring farmers receive fairer compensation for their products. The result is a more equitable distribution of value throughout the food system.

The local-first model also strengthens relationships between producers and consumers. Buyers know the farmers who grow their food, while farmers receive direct feedback regarding quality, freshness, preferred varieties, and seasonal demand. This transparency increases consumer confidence in organic production practices and fosters mutual trust within the community. Such close relationships are rarely possible in long and fragmented supply chains where producers and consumers remain anonymous to one another.

From a food security perspective, prioritising local consumption enhances the village's resilience to market disruptions. During periods of transportation interruptions, fuel shortages, natural disasters, or supply chain disturbances, communities that retain a substantial proportion of their food production locally are better able to maintain access to fresh and

nutritious foods. Short food supply chains therefore contribute not only to economic sustainability but also to community resilience and public health.

Environmental benefits are equally significant. Shorter transport distances reduce fuel consumption and greenhouse gas emissions associated with moving food across long distances. Lower dependence on refrigerated storage and repeated packaging decreases energy use and waste generation. By consuming food closer to where it is produced, Keelara reduces the overall environmental footprint of its agricultural system while promoting more sustainable patterns of production and consumption.

Keelara's approach closely aligns with the principles advocated by the Food and Agriculture Organization (FAO) and other international organisations promoting sustainable food systems. The FAO emphasises that strengthening local and territorial food systems can improve food security, support smallholder farmers, reduce food losses, generate rural employment, and decrease the environmental impacts associated with long-distance transportation. Similarly, the United Nations Sustainable Development Goal (SDG) 12 encourages countries to reduce food losses throughout production and supply chains while promoting sustainable consumption and production practices.

Ultimately, Keelara demonstrates that reversing the conventional food supply chain is not merely a logistical adjustment but a transformation in the philosophy of agricultural development. By placing local nutritional needs before external commercial markets, the village has created a food system that is economically efficient, environmentally sustainable, socially inclusive, and resilient. The model illustrates how rural communities can strengthen local economies, improve farmer livelihoods, reduce food waste, and ensure that the food they produce first nourishes the people who grow it before reaching distant consumers.



## From an Economic Question to a Community-Owned Food System

The findings of the 2016 village economic survey led the members of the Mandya Organic Farmers Cooperative to ask a deceptively simple but fundamentally important question:

**Why should a farming village spend substantial amounts of money purchasing vegetables from outside when its own farmers possess the land, knowledge, and resources to produce fresh, nutritious, and organically grown food?**

This question challenged the prevailing agricultural model in which rural communities primarily cultivate commercial crops for distant markets while relying on external supply chains for their own daily food requirements. Cooperative members argued that such a system weakened the local economy by allowing income generated through agriculture to flow out of the village almost immediately after harvest. Farmers sold their produce through wholesalers and commission agents, but then spent part of those earnings purchasing vegetables, fruits, and other food items supplied by traders from outside the community. Although individual transactions appeared economically rational, their cumulative effect resulted in a continuous outflow of financial resources that could otherwise have strengthened local livelihoods.

Rather than treating this situation as an unavoidable feature of modern agricultural markets, the cooperative viewed it as an opportunity to redesign the village's food economy. The solution they proposed was not merely to establish another retail outlet but to create an institution capable of reconnecting local production with local consumption. This vision resulted in the establishment of the community-owned "Poison Free Vegetable Shop", which later evolved into Keelara's organic produce store.

The store was conceived as a community enterprise rather than a conventional business. Its primary objective was to provide villagers with direct access to fresh vegetables cultivated by neighbouring farmers using organic farming methods while creating a reliable local market for producers. Instead of depending entirely on wholesale markets or distant urban consumers, farmers could sell part of their harvest within their own village, thereby shortening the distance between producer and consumer and reducing dependence on multiple intermediaries.

However, the initiative involved much more than opening a retail outlet. The cooperative encouraged participating households to rethink the structure of their farming systems. Farmers who had previously concentrated almost exclusively on cash crops such as sugarcane or paddy were encouraged to diversify production by allocating portions of their land to vegetables, leafy greens, fruits, pulses, and other food crops. Kitchen gardens and mixed farming practices were promoted so that families could first satisfy their own nutritional requirements before marketing any surplus. This approach represented a significant shift in agricultural priorities. Rather than viewing household food production as secondary to commercial agriculture, the initiative positioned nutritional self-sufficiency as the foundation of sustainable farming.

The emphasis on crop diversification also carried important ecological and nutritional benefits. Growing multiple crops throughout the year improves biodiversity on farms, enhances soil health through diversified cropping systems, and reduces dependence on monoculture production. From a household perspective, diversified cultivation increases access to fresh vegetables and fruits, contributing to improved dietary diversity and reducing the need to purchase these foods from external markets. The cooperative argued that when families consume food grown on their own farms, they not only reduce household expenditure but also



gain greater confidence regarding the quality and cultivation methods of the food they eat.

### **Building a Circular Village Economy**

The establishment of the community-owned organic store reflected a broader economic philosophy centred on strengthening the local circulation of wealth. Economists frequently describe this process through the concept of the local multiplier effect, which explains how money spent within a community generates repeated rounds of economic activity before eventually leaving the local economy. Instead of a single financial transaction ending when a consumer purchases goods, locally retained income continues to circulate among producers, workers, businesses, and service providers, thereby multiplying its overall economic impact.

Prior to the initiative, much of the money spent by Keelara households on vegetables flowed into external supply chains consisting of wholesalers, transporters, commission agents, and urban retailers. Although these supply chains efficiently distributed agricultural products, they also meant that a significant proportion of household expenditure did not directly benefit local farmers. The cooperative sought to reverse this pattern by creating a shorter and more localized marketing system.

In the redesigned system, the economic cycle begins when a village resident purchases vegetables from the community-owned store. Because the produce is sourced from local farmers, a larger proportion of the purchase price remains within the village. Farmers then use this income to buy seeds, organic farm inputs, household goods, labour, livestock feed, or other services from local businesses and neighbours. Shopkeepers, service providers, and labourers subsequently spend their earnings within the village as well, generating additional rounds of economic activity. Through this continuous circulation of money, a single purchase contributes to supporting

multiple livelihoods instead of benefiting only external intermediaries.

The cooperative viewed this circular economic model as a practical strategy for enhancing rural resilience. By increasing local transactions, villages become less vulnerable to fluctuations in transportation costs, disruptions in long-distance supply chains, and volatility in wholesale markets. At the same time, stronger local markets provide farmers with greater marketing flexibility by allowing them to sell part of their produce close to home while continuing to access regional markets for surplus production.

### **Household Savings and Economic Benefits**

According to estimates provided by the Mandya Organic Farmers Cooperative, farming families practising organic cultivation and participating in the community marketing system save approximately ₹32,000 per year through a combination of reduced household expenditure and income earned from selling surplus vegetables locally. These savings arise from several complementary sources. Families consume vegetables, fruits, and leafy greens produced on their own farms, thereby reducing expenditure on food purchases. At the same time, surplus production that might previously have been consumed without generating income—or sold through less profitable marketing channels—can be marketed through the village store, providing an additional revenue stream.

The cooperative argues that these combined economic benefits improve household financial stability while reducing dependence on external markets for essential food items. Nevertheless, comprehensive independent economic research involving larger sample sizes and longitudinal data would be valuable to verify the magnitude of these reported savings and to evaluate their long-term effects on household income, consumption patterns, and rural development. Such studies could also





assess broader economic outcomes, including employment generation, business growth, and changes in local expenditure patterns.

Despite the need for further empirical evaluation, the underlying economic principle is well established within regional development literature. Research on local food systems and community economies suggests that retaining consumer expenditure within local markets can strengthen rural enterprises, increase economic resilience, and generate multiplier effects that exceed the value of the initial transaction. By shortening supply chains and strengthening producer-consumer relationships, locally owned food systems often contribute to more equitable distribution of economic benefits while supporting community development.

### **Agriculture Beyond Commercial Production**

Perhaps the most significant contribution of the Keelara initiative lies in its redefinition of the purpose of agriculture. Instead of viewing farming exclusively as a commercial activity aimed at maximizing sales in distant markets, the initiative promotes a more integrated understanding in which agriculture simultaneously fulfills economic, nutritional, environmental, and social functions. Food production becomes not only a source of income but also a means of ensuring household food security, improving dietary diversity, conserving natural resources, and strengthening community relationships.

This perspective aligns with broader concepts of sustainable rural development and food sovereignty, which emphasize the importance of local communities having greater control over their food systems. By encouraging villages to meet a significant share of their own food requirements before exporting surplus production, the Keelara model seeks to balance market participation with local self-reliance. Farmers continue to engage with commercial markets where appropriate, but

household nutrition and community well-being become equally important objectives of agricultural production.

Ultimately, what began as a straightforward economic question evolved into a comprehensive model of community-based development. The establishment of the Poison Free Vegetable Shop and its evolution into a community-owned organic store demonstrated how local institutions can address multiple challenges simultaneously—including economic leakage, food insecurity, limited market access, and environmental sustainability. By reconnecting local production with local consumption and promoting the circulation of wealth within the village, Keelara offers an example of how community-driven initiatives can contribute to building more resilient, inclusive, and sustainable rural economies.

### **Why the Keelara Village Model Matters**

#### **1. Why Food Miles Matter**

One of the most important environmental benefits of the Keelara initiative is its ability to reduce food miles. Food miles refer to the total distance food travels from where it is produced to where it is consumed. In conventional food systems, vegetables often pass through several stages before reaching consumers. They are transported from farms to wholesale markets, then to processing or packaging centres, distribution warehouses, retailers, and finally to households. Each stage requires transportation, fuel, refrigeration, packaging, and handling, all of which increase greenhouse gas emissions and energy consumption.

Research published in the journal *Nature Food* found that food transportation contributes approximately 19% of the greenhouse gas emissions associated with global food systems. Although food production itself remains the largest source of emissions, transport—particularly long-distance trucking and air freight—





adds significantly to agriculture's environmental footprint.

Keelara addresses this issue by creating a localised food system. Vegetables harvested by farmers are sold directly to the village store, often travelling only a few hundred metres or a few kilometres. This dramatically reduces the need for trucks, repeated loading and unloading, cold storage, and excessive packaging. Only surplus produce intended for urban consumers enters longer supply chains.

While the Mandya Organic Farmers Cooperative has not published specific carbon-emission data for Keelara, the model aligns with internationally recognised principles of low-carbon local food systems, which encourage local production and consumption to reduce environmental impacts.

## 2. Organic Farming as a Community Practice

Unlike many commercial organic farms that mainly supply export markets or premium urban consumers, Keelara integrates **organic farming into everyday village life**. The initiative encourages families to grow a wide variety of vegetables throughout the year rather than concentrating on a single cash crop.

This diversified farming system offers several important benefits:

- **Improved nutrition:** Families have access to many different vegetables, resulting in a more balanced and nutritious diet.
- **Healthier soils:** Different crops use nutrients differently and help maintain soil fertility.
- **Greater biodiversity:** Growing multiple crops supports insects, birds, and beneficial microorganisms that contribute to healthier ecosystems.
- **Natural pest management:** Crop diversity interrupts pest life cycles and reduces dependence on chemical pesticides.

- **Reduced dependence on purchased food:** Families become more self-sufficient by producing a larger share of their own food.

In Keelara, farming is viewed not merely as an income-generating activity but as a foundation for **public health, environmental sustainability, and community well-being**. This philosophy reflects the principles of agroecology, which integrates ecological science with sustainable agriculture and community development.

## 3. Collective Ownership Instead of Corporate Retail

A unique feature of the Keelara initiative is its community-owned governance structure. Instead of being operated by a private supermarket chain or an outside company, the village organic store belongs to the community through the Mandya Organic Farmers Cooperative.

In this cooperative model:

- Farmers supply vegetables directly to the store.
- Farmers also participate as stakeholders in decision-making.
- The cooperative manages procurement, quality control, pricing, storage, and marketing.
- Decisions are made collectively, ensuring that farmers' interests remain central.

This structure provides several advantages:

- **Greater bargaining power:** Farmers negotiate collectively rather than individually.
- **Reduced dependence on middlemen:** Commission agents take a smaller share of farmers' earnings.



- **Lower transaction costs:** Collective marketing improves efficiency.
- **Fairer income distribution:** More of the consumer's payment reaches the producer.

Globally, agricultural cooperatives are recognised as effective institutions for strengthening rural economies, improving market access, and increasing resilience among small-scale farmers. Keelara adapts these cooperative principles to meet the growing demand for locally produced organic food while ensuring that economic benefits remain within the community.

#### 4. Strengthening Nutrition and Food Security

The Keelara model also addresses an important but often overlooked issue in farming communities. In many agricultural regions, farmers sell their highest-quality produce to urban markets because cities offer better prices. As a result, farming families sometimes consume cheaper, less nutritious food despite producing healthy crops themselves.

Keelara deliberately reverses this pattern by **giving local residents priority access to fresh organic vegetables** before surplus produce is sold outside the village.

This approach provides several benefits:

- **Improved household nutrition:** Families, children, and elderly residents consume fresher and healthier food.
- **Greater food security:** The community becomes less dependent on food imported from distant markets.
- **Protection from market fluctuations:** Local availability reduces the impact of sudden price increases.
- **Resilience during disruptions:** During fuel shortages, transport problems, extreme weather, or supply-chain interruptions, the

village can continue meeting much of its own food needs.

The concept reflects the broader goals of food security, defined by the FAO as ensuring that all people have physical, social, and economic access to sufficient, safe, and nutritious food at all times.

Local food systems such as Keelara contribute to all four dimensions of food security:

- Availability
- Accessibility
- Utilisation (nutrition)
- Stability over time

By prioritising local consumption before external sales, Keelara strengthens both community health and resilience against economic or environmental shocks.

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The Keelara initiative demonstrates how a community-based organic food system can simultaneously address environmental sustainability, rural livelihoods, nutrition, and food security. By reducing food miles, promoting diversified organic farming, operating through a farmer-owned cooperative, and prioritising local consumption, the model creates a resilient and low-carbon food system. Rather than treating agriculture solely as a commercial activity, Keelara places food production at the centre of community health, environmental stewardship, and sustainable rural development. This integrated approach makes it an example of how local food systems can contribute to broader goals such as climate change mitigation, sustainable agriculture, and improved quality of life.

#### Challenges That Cannot Be Ignored

Although the Keelara model has demonstrated significant success in strengthening local food



systems, improving farmer incomes, and promoting organic agriculture, it also faces several important challenges that must be addressed for its long-term sustainability and wider adoption.

### 1. Ensuring a Consistent Supply of Vegetables

One of the biggest challenges is maintaining a continuous and diverse supply of fresh vegetables throughout the year. Consumers expect the availability of different vegetables in every season, but agricultural production is naturally influenced by weather conditions, rainfall patterns, pests, and seasonal cycles.

**To meet market demand, farmers must carefully coordinate:**

- Crop planning
- Sowing schedules
- Harvest timings
- Crop diversification

This requires strong cooperation among all participating farmers. If too many farmers grow the same crop simultaneously, oversupply can reduce prices and increase waste. Conversely, inadequate planning may lead to shortages that force the store to purchase vegetables from outside sources, weakening the objective of local self-reliance.

### 2. Challenges of Organic Farming

Organic farming offers many environmental and health benefits, but transitioning from conventional agriculture is often difficult.

#### Higher Labour Requirements

Organic farming depends heavily on manual activities such as:

- Hand weeding
- Compost preparation

- Biological pest management
- Crop rotation
- Mulching

These activities require more labour than conventional farming, increasing production costs, especially where labour shortages exist.

#### Lower Initial Yields

During the conversion period from conventional to organic farming, soil biology takes time to recover. As a result, crop yields may decline for the first few years before stabilising. This temporary reduction in productivity can discourage farmers who depend on regular income.

#### Certification Costs

Obtaining and maintaining organic certification can involve inspections, documentation, and compliance costs that may be difficult for small farmers unless cooperative organisations provide assistance.

### 3. Consumer Awareness and Acceptance

Another major challenge is educating consumers about the characteristics of organic vegetables.

Unlike conventionally grown produce, organic vegetables often:

- vary in size,
- have irregular shapes,
- contain minor insect marks,
- or appear less visually attractive.

Many consumers mistakenly associate perfect appearance with better quality. In reality, cosmetic imperfections do not affect nutritional value or safety.

Therefore, continuous awareness campaigns are necessary to explain:



- the benefits of organic farming,
- the absence of harmful chemical residues,
- and the fact that natural variation is normal in organically grown crops.
- timely payments,
- transparent decision-making,
- and long-term economic benefits for members.

Building consumer trust is essential for sustaining demand.

#### 4. Scaling the Model to Other Villages

Expanding the Keelara model to other regions is not simply a matter of opening more retail stores.

Its success depends on several social and institutional factors, including:

- Strong farmer cooperatives
- Community participation
- Transparent governance
- Reliable quality control
- Fair pricing systems
- Mutual trust among members
- Long-term farmer commitment

These social structures are often more difficult to establish than the physical infrastructure itself. Villages with weak community organisations or internal conflicts may struggle to replicate the model successfully.

#### 5. Maintaining Farmer Participation

Farmers may occasionally receive higher prices from private traders during periods of market shortages. If many farmers choose to sell outside the cooperative, the local retail system may experience supply shortages.

To prevent this, cooperatives must ensure:

- competitive prices,

Maintaining farmer confidence is critical for the sustainability of the model.

#### A Model with Global Relevance

The Keelara model reflects broader international efforts to create sustainable, localised food systems that reduce environmental impacts while improving farmer livelihoods.

#### Global Interest in Short Food Supply Chains

Across the world, governments and development organisations increasingly support short food supply chains, where food moves directly from producers to consumers with minimal intermediaries.

These systems offer several advantages:

- Reduced transportation costs
- Lower greenhouse gas emissions
- Fresher produce
- Greater transparency
- Higher farmer incomes
- Stronger local economies

#### International Examples

##### European Union

The European Union promotes short food supply chains through its Common Agricultural Policy (CAP), encouraging farmers to sell directly to consumers, schools, restaurants, and local markets. These initiatives strengthen rural economies while reducing environmental impacts.



## North America

Community-Supported Agriculture (CSA) programmes allow consumers to purchase seasonal subscriptions directly from farmers. This guarantees farmers a stable income while providing consumers with fresh local produce throughout the growing season.

## Japan

Japan's Teikei Movement, which began in the 1970s, established direct partnerships between farmers and consumers based on mutual trust, shared responsibility, and local food production. It became one of the earliest successful models of community-supported agriculture.

## Farmers' Markets Worldwide

Many countries have expanded farmers' markets where producers sell directly to consumers. These markets strengthen local economies while reducing dependence on large retail chains.

## Keelara's Unique Indian Approach

Although similar in spirit to these international models, Keelara has its own distinctive characteristics.

Unlike systems based mainly on private entrepreneurship, Keelara emphasises:

- cooperative ownership,
- village self-reliance,
- collective decision-making,
- local food security,
- and community participation.

Rather than focusing solely on exporting agricultural products or competing in distant markets, the village first ensures that local nutritional needs are met before selling surplus produce elsewhere.

This reflects the broader principles of sustainable rural development by integrating:

- economic resilience,
- environmental conservation,
- and social cooperation.

## Lessons for Rural India

The Keelara model provides valuable insights for strengthening rural agriculture across India.

### 1. Prioritising Local Food Security

Meeting local food requirements before marketing surplus produce improves nutritional security and reduces dependence on external markets.

### 2. Community-Owned Retail Systems

Village-owned retail outlets keep profits within the community instead of transferring wealth to external intermediaries. This supports local economic development and creates employment opportunities.

### 3. Shorter Supply Chains

Reducing the distance between producers and consumers lowers transportation costs, minimises food waste, decreases carbon emissions, and ensures fresher vegetables for consumers.

### 4. Stronger Farmer Bargaining Power

Cooperative marketing enables farmers to negotiate better prices, reduce exploitation by middlemen, and improve income stability through collective action.

### 5. Economic Viability of Organic Farming

Organic farming becomes financially sustainable when farmers have assured local markets willing to purchase their produce at fair prices. Stable demand encourages more farmers to adopt environmentally friendly practices.





## 6. Complementing National Agricultural Policies

Village-level initiatives like Keelara do not replace government agricultural programmes. Instead, they complement national policies by demonstrating how local communities can actively contribute to food security, sustainable agriculture, rural employment, and climate resilience.

The Keelara model illustrates how cooperative ownership, organic farming, and short food supply chains can transform rural agriculture. While challenges such as maintaining year-round production, encouraging consumer awareness, managing organic transition, and building strong community institutions remain significant, the model offers a practical pathway toward sustainable development. Its success demonstrates that strengthening local food systems can simultaneously improve farmer incomes, enhance food security, reduce environmental impacts, and build resilient rural communities. As India and many other countries seek sustainable agricultural solutions, the lessons from Keelara provide a valuable example of how community-driven initiatives can complement broader agricultural policies and contribute to long-term rural prosperity.

### Looking Ahead

As India confronts the intertwined challenges of climate change, rising input costs, declining farm incomes, and growing concerns about food quality, initiatives such as Keelara demonstrate that innovation need not always come from large corporations or advanced technologies.

**Sometimes it begins with a village asking a simple question:**

**Why should food grown here travel hundreds of kilometres before feeding the people who cultivate it?**

Keelara's answer is a community-owned store that reconnects farmers with consumers, keeps wealth circulating locally, and reimagines agriculture not merely as a commercial enterprise but as the foundation of community resilience.

Further independent research is needed to evaluate the model's long-term economic, nutritional, and environmental outcomes. Nevertheless, Keelara provides a compelling case study of how locally governed food systems can contribute to more sustainable rural development—one harvest, one household, and one village at a time.

As India moves further into the twenty-first century, its agricultural sector faces several interconnected challenges. Climate change has made rainfall patterns increasingly unpredictable, causing frequent droughts, floods, heatwaves, and pest outbreaks. At the same time, the prices of agricultural inputs such as chemical fertilisers, pesticides, seeds, diesel, and labour continue to rise, increasing production costs for farmers. Many small and marginal farmers also struggle with unstable market prices, limited bargaining power, and declining incomes. Alongside these economic concerns, consumers are becoming more aware of food safety, nutrition, and the health risks associated with excessive chemical use in agriculture.

Against this complex backdrop, the Keelara model demonstrates that meaningful agricultural innovation does not always require expensive technologies, large corporate investments, or massive government programmes. Instead, effective solutions can emerge from local communities that understand their own needs and work collectively to address them. Keelara shows that simple organisational innovations—such as establishing a community-owned retail store and strengthening direct links between farmers and consumers—can produce significant economic, environmental, and social benefits.



At the heart of the Keelara initiative lies a simple but powerful question:

**"Why should food grown here travel hundreds of kilometres before feeding the people who cultivate it?"**

This question challenges the conventional food supply system, where vegetables often pass through multiple intermediaries before reaching consumers. In traditional marketing systems, produce may be transported to wholesale markets, redistributed through traders, and eventually sold in distant urban centres. Ironically, the same vegetables sometimes return to nearby villages through retail shops at higher prices. This long journey increases transportation costs, fuel consumption, food waste, and carbon emissions while reducing the share of income received by farmers.

Keelara offers a practical alternative by creating a community-owned retail store that allows farmers to sell their vegetables directly within their own village. Instead of relying heavily on external markets, locally grown produce first satisfies the nutritional needs of the local community. Consumers receive fresh, seasonal, and organically grown vegetables at reasonable prices, while farmers earn a larger share of the final selling price because fewer intermediaries are involved.

Another important feature of the model is that it keeps wealth circulating within the local economy. Money spent by village residents remains within the community rather than flowing to outside traders or large retail chains. Farmers earn higher incomes, local employment opportunities increase through the operation of the retail store, and the economic benefits are shared among cooperative members. This circulation of local income strengthens the village economy and enhances its resilience during periods of market uncertainty.

The Keelara model also redefines agriculture. Rather than viewing farming solely as a commercial activity

focused on maximizing production and profits, it presents agriculture as the foundation of community resilience. In this approach, farming contributes not only to economic growth but also to food security, public health, environmental conservation, and social cooperation. Agriculture becomes a system that supports the wellbeing of the entire community rather than merely producing commodities for distant markets.

The emphasis on organic farming further strengthens this vision. By reducing dependence on synthetic fertilisers and pesticides, farmers help improve soil fertility, conserve biodiversity, protect water resources, and reduce pollution. Consumers benefit from access to fresh vegetables produced using environmentally sustainable methods. Over time, healthier soils may become more resilient to climate-related stresses such as droughts and heavy rainfall, contributing to long-term agricultural sustainability.

Despite these promising outcomes, the Keelara model should not be viewed as a complete solution to all agricultural challenges. Its long-term effectiveness requires careful evaluation through independent scientific research. Researchers can examine several important questions, including:

- Does the model consistently improve farmers' incomes over many years?
- How does participation affect household nutrition and dietary diversity?
- Does organic cultivation improve soil health and biodiversity over time?
- Can the cooperative remain financially sustainable without continuous external support?
- How effectively can the model be adapted to villages with different social, economic, and environmental conditions?



- What governance structures are necessary to maintain transparency and community participation?

Such research would provide valuable evidence for policymakers, development organisations, and rural communities considering similar initiatives.

The lessons from Keelara also have broader policy implications. Governments can encourage similar local food systems by supporting farmer cooperatives, investing in village-level storage and retail infrastructure, providing training in organic agriculture, facilitating certification, and promoting consumer awareness of locally produced food. Such measures could complement national agricultural programmes while strengthening rural livelihoods and environmental sustainability.

In conclusion, Keelara represents more than a successful village retail initiative; it serves as a model of community-led sustainable development. It demonstrates that local ownership, cooperative action, shorter food supply chains, and environmentally responsible farming can work together to address some of the most pressing challenges facing modern agriculture. Although further research is needed to assess its long-term economic, nutritional, and ecological impacts, Keelara offers an inspiring example of how locally governed food systems can strengthen rural resilience. Its experience suggests that sustainable agricultural transformation can begin at the grassroots level—one harvest, one household, and one village at a time.

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# Molecular Diagnostics in *Bombyx mori*: Revolutionizing Disease Detection

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Silk has fascinated humanity for thousands of years with its unmatched beauty, strength, and elegance. Behind every shimmering silk thread lies a tiny insect-the domesticated silkworm, *Bombyx mori*. In India, sericulture provides employment to millions of rural families and contributes significantly to the country's economy. Yet this remarkable insect faces an invisible enemy: infectious diseases that can devastate silkworm crops within days, leading to severe economic losses. Today, advances in molecular biology are transforming the way these diseases are detected and managed. From conventional microscopic examination to sophisticated CRISPR-based diagnostics, scientists are equipping the sericulture industry with faster, more accurate tools to protect silkworm health and ensure sustainable silk production.

## The Invisible Threat to Silk Production

Silkworms are highly susceptible to infections caused by viruses, bacteria, fungi, and microsporidia. Because they are reared under warm and humid conditions, pathogens can spread rapidly through the rearing house, infecting large numbers of larvae before symptoms become visible.

Among the major diseases affecting *Bombyx mori* are:

**Pebrine**, caused by the microsporidian parasite *Nosema bombycis*, is perhaps the most feared disease in sericulture. The parasite is transmitted both vertically-from infected female moths to their eggs-and horizontally through contaminated food and rearing equipment. Infected larvae exhibit poor growth, irregular moulting, reduced feeding, and

ultimately produce inferior cocoons or die before spinning.

**Grasserie**, caused by *Bombyx mori* nucleopolyhedrovirus (BmNPV), results in swollen, fragile larvae filled with viral particles. Diseased worms often burst easily, contaminating the surroundings and accelerating disease spread.

**Flacherie** is a complex disease involving bacterial infections, viral agents, or environmental stress. Affected larvae become soft, lethargic, and eventually decay, causing heavy crop losses.

**Muscardine**, mainly caused by the fungus *Beauveria bassiana*, covers dead larvae with a characteristic white fungal growth. The disease spreads rapidly under humid conditions and can destroy an entire rearing batch if not controlled promptly.

Since the external symptoms of these diseases often overlap, rapid and accurate diagnosis is essential for effective disease management.

## Conventional Methods: The Foundation of Disease Diagnosis

Long before molecular biology entered the sericulture laboratory, disease diagnosis relied on careful observation and microscopy.

For pebrine, one of the oldest and still widely practiced methods is mother moth examination. After egg laying, the female moth is crushed and examined under a microscope for the presence of *Nosema* spores. Egg batches from infected moths are discarded to prevent transmission of the parasite to the next generation. Microscopic examination



remains inexpensive and relatively simple, making it suitable for routine screening. However, it requires trained personnel and may fail to detect infections when the spore count is very low. Other diseases are usually diagnosed by observing characteristic symptoms, examining diseased tissues microscopically, or isolating pathogens using microbiological techniques. Although these conventional approaches have served the sericulture industry for decades, they often require visible symptoms to develop, delaying intervention and increasing the risk of disease spread.

### **Molecular Diagnostics: Detecting Disease at the Genetic Level**

The emergence of molecular diagnostics has revolutionized disease detection by targeting the genetic material of pathogens rather than relying solely on visible symptoms.

#### **Polymerase Chain Reaction (PCR)**

Polymerase Chain Reaction (PCR) has become one of the most reliable laboratory techniques for diagnosing silkworm diseases. By amplifying pathogen-specific DNA sequences, PCR can detect extremely small quantities of infectious agents. PCR assays have been developed for identifying *Nosema bombycis*, BmNPV, cytoplasmic polyhedrosis virus (BmCPV), *Beauveria bassiana*, and several bacterial pathogens. Compared with conventional microscopy, PCR offers greater sensitivity and specificity, allowing early diagnosis before obvious clinical symptoms appear. This early detection enables sericulture laboratories to remove infected seed lots and implement timely disease control measures.

#### **Quantitative Real-Time PCR (qPCR)**

While conventional PCR confirms the presence of a pathogen, quantitative real-time PCR (qPCR) goes one step further by measuring the amount of pathogen present. Using fluorescent probes, qPCR monitors DNA amplification in real time and

estimates pathogen load within a sample. This information helps researchers evaluate disease progression, compare infection levels among silkworm batches, and assess the effectiveness of disease management practices. Because of its high sensitivity and rapid turnaround, qPCR has become an important tool in disease surveillance and research laboratories.

#### **Rapid Detection with Lateral Flow Assays**

Although PCR-based methods are highly accurate, they require specialized equipment and trained personnel. This has driven the development of simple, field-friendly diagnostic tools.

**Lateral flow assays (LFAs):** similar in appearance to home pregnancy tests—are emerging as valuable tools for rapid pathogen detection. These portable strips use antibodies or nucleic acid probes to recognize specific pathogen molecules and produce a visible coloured line within minutes. Lateral flow tests require minimal sample preparation, do not depend on sophisticated laboratory infrastructure, and can be performed directly at grainages or rearing centres. Their simplicity makes them particularly attractive for routine disease monitoring in rural sericulture systems.

#### **CRISPR: The Next Generation of Disease Diagnostics**

The newest frontier in molecular diagnostics involves the revolutionary CRISPR technology. Although CRISPR is widely known for genome editing, certain CRISPR-associated proteins such as Cas12 and Cas13 possess remarkable diagnostic capabilities. Platforms such as DETECTR and SHERLOCK combine CRISPR enzymes with simple nucleic acid amplification methods to detect pathogen DNA or RNA with extraordinary sensitivity. When the target sequence is present, the activated CRISPR enzyme cleaves specially designed reporter molecules, generating an easily detectable fluorescent or colourimetric signal. Some





CRISPR-based assays can even be combined with lateral flow strips, allowing rapid visual detection without expensive instruments. For silkworm disease diagnosis, CRISPR-based platforms hold enormous promise. They offer rapid detection, exceptional specificity, and the potential for portable, point-of-care testing that could be deployed directly in sericulture farms. Although many applications remain at the research stage, these technologies are expected to become valuable tools for disease surveillance in the near future.

### **Toward Smarter Sericulture**

The future of silkworm disease diagnosis lies in integrating multiple technologies. Portable DNA extraction systems, isothermal amplification methods, CRISPR diagnostics, smartphone-based readers, and artificial intelligence are expected to create compact diagnostic platforms capable of identifying pathogens within an hour. Such innovations will enable farmers to make informed management decisions, reduce unnecessary losses, improve cocoon quality, and ensure the production of disease-free silkworm seed.

### **Conclusion**

Healthy silkworms are the foundation of a thriving silk industry. While conventional microscopic methods continue to play an important role, modern molecular diagnostics have dramatically improved our ability to detect diseases early and accurately. PCR and qPCR have become indispensable laboratory tools, lateral flow assays are bringing diagnostics closer to the field, and CRISPR technology promises an exciting future of rapid, highly sensitive, and portable disease detection. As these technologies become more affordable and accessible, they will strengthen disease surveillance, improve farmer confidence, and contribute to a more resilient and sustainable sericulture sector. In the journey from mulberry leaf to silk fabric, molecular diagnostics is proving to be one of the most valuable threads connecting science with sustainable silk production.

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# The Role of Indian Reservoirs in Fish Production and Livelihood Security

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## Why Reservoir Fisheries Matter

Among India's most valuable inland aquatic resources, reservoir fisheries are essential to rural development, employment, food security, and biodiversity preservation. With hundreds of small, medium, and large reservoirs contributing more than 3.5 million hectares of reservoir water. India has tremendous potential for sustainable fish production. In contrast to marine fisheries, reservoir fisheries give millions of people who live distant from coastal areas a consistent supply of freshwater fish. Through fish seed production, shipping, marketing, capture fisheries, and culture-based fisheries, they help sustain the livelihoods of fishing communities.

By producing revenue while preserving ecological equilibrium, reservoirs play a major role in the nation's Blue Economy. Numerous aquatic animals use them as breeding and rearing grounds, and they offer habitat to a variety of native and commercially significant fish species. Fish production has increased in many reservoirs thanks to scientific management techniques such stock enhancement, habitat development, controlled fishing, and water quality monitoring.

Reservoir fisheries are now crucial for maintaining nutritional security and sustainable resource use due to the rising demand for animal protein and the mounting strain on natural resources. They have long-term positive effects on the economy, ecology, and society when properly managed. Reservoir fisheries are therefore important natural resources that greatly support India's sustainable fisheries development rather than just being pools of water for electricity and irrigation.

## From Water Bodies to Food Bowls

Indian reservoirs are essential for providing millions of households with wholesome freshwater fish. Because it contains high-quality protein, omega-3 fatty acids, vitamins, and vital minerals, fish is regarded as one of the healthiest animal protein sources. Large freshwater resources are transformed into productive ecosystems by reservoir fisheries, which greatly enhance the country's food and nutritional security.

Commercially significant species including Catla (*Catla catla*), Rohu (*Labeo rohita*), Mrigal (*Cirrhinus mrigala*), Mahseer (*Tor spp.*), Catfishes, Minor carps, and a number of native fishes are produced in reservoirs. In many reservoirs, fish yields have increased because of scientific fish seed supply, habitat improvement, and ethical harvesting methods. In addition to guaranteeing a consistent supply of fresh fish in regional markets, improved fish production opens possibilities for processing and value addition.

The need for reasonably priced, healthful protein is rising quickly as India's population continues to expand. By offering locally accessible fish at fair rates, easing the strain on marine resources, and encouraging balanced diets, reservoir fisheries aid in closing this disparity. Reservoirs therefore efficiently transform freshwater resources into food resources, enhancing nutritional security and promoting rural livelihoods and sustainable fisheries.

## How Reservoirs Support Rural Economies

Thousands of households depend on reservoir fisheries for work and income, especially in rural and



tribal areas where there aren't many other options. Fishing creates jobs for fishermen directly as well as indirectly through the manufacture of fish seeds, nets, boats, transportation, fish processing, ice, and marketing. A thriving rural economy connected to fishing is produced by these various activities.

Self-help organizations and fishers' cooperative societies are crucial for managing fishing operations, guaranteeing fair benefit distribution, and expanding market access. Women make substantial contributions to household income and financial stability through their active participation in fish processing, drying, packaging, retail marketing, and other post-harvest activities.

Reservoir fisheries revenue raises living standards by funding housing, nutrition, healthcare, and education. Fisheries are now a useful instrument for social development and poverty reduction in many areas. The economic potential of reservoir fisheries is further strengthened by government measures, such as infrastructure support, skill development programs, and financial aid.

Reservoir fisheries support sustainable rural development by generating year-round jobs and fostering entrepreneurship. Reservoirs are a key component of equitable growth and livelihood security in India's inland regions because they also boost regional companies and foster economic resilience.

### **Balancing Fish Production and Conservation**

To guarantee the long-term viability of reservoir ecosystems, increasing fish output should always be accompanied by efficient conservation measures. Fish variety and productivity are threatened by unsustainable fishing methods, overharvesting, pollution, invasive species, habitat deterioration, and climate change. Thus, it is crucial to strike a balance between ecological preservation and economic gains.

Maintaining ideal stocking levels, controlling fishing seasons, enforcing minimum mesh sizes, safeguarding breeding areas, preserving local fish species, and regularly checking water quality are all components of scientific fisheries management. These actions enable reservoirs to continue being productive throughout time while assisting in the maintenance of healthy fish populations. Reservoir health is further enhanced by pollution management, catchment area afforestation, and habitat restoration.

Maintaining aquatic biodiversity especially depends on the conservation of native species like mahseer and other fish. Ecosystem-based fisheries management acknowledges that sustainable fish production depends on balanced food webs, healthy habitats, and clean water.

Strong enforcement of fisheries laws, community involvement, and public awareness promote ethical fishing methods and lessen illicit exploitation. Reservoir fisheries can effectively achieve both increased productivity and biodiversity conservation by combining scientific knowledge with traditional wisdom. Present and future generations will continue to benefit from reservoir resources thanks to sustainable management.

### **Empowering Fishers Through Sustainable Management**

Reservoir fisheries rely heavily on fishermen, and sustainable resource management depends on their active involvement. Fish production and livelihood security are enhanced when fishing communities are empowered through institutional development, financial support, education, and training. Programs to increase capacity assist fishermen in implementing sustainable harvesting practices, scientific fishing methods, better post-harvest processing, and contemporary fish marketing strategies.

The establishment of fishers' cooperatives improves access to credit, boosts collective decision-making, and gives them more negotiating leverage in



marketplaces. Economic stability is further improved by government programs like insurance plans, cold storage, financial aid for boats, fishing equipment, and fish seed stocking. Weather forecasting services, GPS-based navigation, and mobile applications are examples of digital technology that help fishermen make better judgments and increase operational efficiency.

Responsible ownership of reservoir resources is promoted by community involvement in fisheries management, habitat conservation, and resource monitoring. Through their entrepreneurial endeavours in fish processing, value addition, ornamental fisheries, and aquaculture-related businesses, women and young people also play an increasingly significant role.

Reservoir fisheries become more robust, productive, and sustainable when fishermen take on a collaborative role in conservation rather than just using resources. Thus, long-term livelihood security and fisheries governance are strengthened by empowering local populations.

### **The Way Forward for India's Reservoir Fisheries**

India's reservoir fisheries have vast, unrealized potential that might play a major role in future employment creation, food security, and sustainable economic growth. It will take scientific planning, robust policy backing, community involvement, and ongoing technology innovation to realize this potential. The development of reservoir fisheries should incorporate ecosystem-based management,

prudent stocking programs, habitat rehabilitation, and regular fish stock assessments.

Fisheries planning and resource evaluation can be enhanced by contemporary technology including digital monitoring systems, drones, GIS, remote sensing, and artificial intelligence. Rising temperatures, shifting rainfall patterns, and variations in water level that impact fish output should all be addressed by climate-resilient management measures. Profitability will rise and post-harvest losses will decrease with increased investment in cold-chain infrastructure, processing facilities, value addition, and fish seed quality.

More equitable and sustainable fisheries will be produced by bolstering fishers' cooperatives, supporting women-led businesses, boosting youth involvement, and growing training initiatives. Working together, local communities, government organizations, and research institutions can promote adaptive management and evidence-based decision-making.

India's reservoir fisheries can become a potent pillar of the Blue Economy with responsible governance and scientific management, protecting these priceless resources for future generations while guaranteeing healthy aquatic ecosystems, increased fish production, better nutrition, and secure livelihoods for millions of people.

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## Empowering Rural Prosperity Through Scientific Cold Storage Infrastructure: Inspiring Success Story of Women Entrepreneurs

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In the agricultural heartland of Yerragudi Village, Moka Hobli, Bellary District of Karnataka, an inspiring success story of women entrepreneurship and agricultural transformation is unfolding. Visionary entrepreneurs Smt. Pallavi Pacharalli and Smt. Satyavani Kuruvalli, Directors of M/s Bhadra Cold Storage Pvt. Ltd, have emerged as pioneers in scientific post-harvest management through the establishment of a modern cold storage facility under the National Horticulture Board (NHB) Capital Investment Subsidy Scheme for construction/Expansion/Modernization of cold storage for horticulture products.



Their journey reflects how innovation, determination, and institutional support can revolutionize the storage and marketing of horticultural produce, particularly dry chillies and tamarind, while generating substantial employment and income opportunities in rural Karnataka.

### The Beginning of a Visionary Journey

The entrepreneurial journey of Smt. Pallavi Pacharalli and Smt. Satyavani Kuruvalli began with a clear vision to create modern cold storage infrastructure capable of preserving the quality,

colour, and market value of dry chillies and other horticultural commodities for extended periods.

Prior to establishing the cold storage facility, the promoters were associated with traditional chilli cultivation under open-field conditions. However, they faced several challenges including fluctuating market prices, post-harvest losses, quality deterioration, and reduced profitability. After learning about the benefits offered under NHB schemes, they recognized the immense potential of scientific storage infrastructure in addressing these challenges and decided to establish hitech cold storage unit.



Accordingly in the year 2023 to 2024, they established M/s Bhadra Cold Storage Pvt. Ltd. at Yerragudi Village, Moka Hobli, Bellary District, Karnataka-583103, with a storage capacity of 9,870 MT comprising three chambers designed as per NHB technical standards and specifications.

### Modern Infrastructure and Technological Excellence

The success of the project was driven by the adoption of advanced cold storage technology and modern





infrastructure developed strictly in accordance with NHB norms.

The cold storage facility was established as a Type-I cold storage unit with mezzanine flooring and equipped with advanced refrigeration and safety systems to ensure long-term preservation of dry chillies, tamarind and other horticultural commodities without colour change, quality deterioration or weight loss.

The facility includes:

- High-quality insulation systems
- Direct expansion refrigeration technology using HFC (Freon) refrigerant
- Scroll-type compressors with air-cooling units
- Five cooling units with dual-fan arrangements in each chamber
- Modern lift systems
- Electronic weighing facilities
- Firefighting systems including CO<sub>2</sub> and water-based safety mechanisms
- Distribution and control panel boards
- Power factor correction systems
- Transformer and DG set backup facilities, through these modern technologies, the entrepreneurs ensured efficient storage management, reduced post-harvest losses and maintained superior product quality throughout the storage period.



### Financial Support and Institutional Assistance

The establishment of the cold storage project required substantial financial investment and careful planning. The total project cost amounted to Rs. 815.00 lakh. Out of this Rs. 580.00 lakh was sanctioned as a term loan by Canara Bank, Bellary Main Branch and Rs. 234.53 lakh was contributed by the promoters from their own resources

The project received critical support from the National Horticulture Board in the form of a 35% capital investment subsidy amounting to Rs. 234.90 lakh, which significantly strengthened the financial viability of the project and enabled the entrepreneurs to successfully implement the modern infrastructure. In addition to the cold storage project, the entrepreneurs also established a solar power unit to improve energy efficiency and reduce electricity costs.





The solar project involved a total investment of Rs. 61.98 lakh of which, Rs. 47.50 lakh was financed through a term loan from Canara Bank and Rs. 14.48 lakh was invested by the promoters. Recently during March 2026, NHB approved 35% subsidy of Rs. 12.25 lakh under the scheme no.2. further supporting sustainable and energy-efficient operations.

### Remarkable Business Success and Profitability

The cold storage venture has delivered outstanding financial results and emerged as a highly successful agribusiness model in the region. The cold storage facility provides local as well as other farmers with scientific storage facilities for preserving major commodities such as dry chillies and tamarind on a rental basis throughout the season. Through rental services and trading activities, the cold storage unit generates an impressive gross annual income of nearly Rs. 161.50 lakh annually. By adopting efficient storage management practices and advanced scientific preservation techniques, the entrepreneurs are earning an estimated net profit of around Rs. 31.00 lakh per year from the 9,870 MT cold storage facility.



The entrepreneurs attribute their success to:

- Timely financial assistance from NHB
- Scientific storage infrastructure
- Efficient operational management
- Strong market demand for quality-preserved produce
- Adoption of modern technology and energy-efficient systems, Their achievement demonstrates how modern post-harvest infrastructure can substantially enhance profitability and sustainability in the horticulture sector.

### Employment Generation and Rural Development

Apart from financial success, the project has made a significant contribution to local employment generation and rural economic development.

The cold storage unit has created employment opportunities for more than 125 local people during operational activities and provides permanent employment to around 15 staff members working in various capacities such as Managers, Technicians, Cashier, Machine operators, Support staff etc. The enterprise has thus become an important source of livelihood and economic empowerment for many families in the surrounding region.



## A Model for Women Entrepreneurship in Agriculture

The inspiring success of Smt. Pallavi Pacharalli and Smt. Satyavani Kuruvalli stands as a remarkable example of women-led entrepreneurship in the agricultural infrastructure sector. Their determination, innovative thinking and effective utilization of government support schemes have transformed a visionary idea into a thriving enterprise.

Their story highlights the critical role of scientific post-harvest management in reducing losses, improving product quality, enhancing farmers' incomes, and strengthening the horticulture value chain.

Most importantly, it serves as a powerful inspiration for aspiring women entrepreneurs and progressive farmers across the country to embrace technology-driven agriculture and infrastructure development.

## Conclusion

The success story of M/s Bhadra Cold Storage Pvt. Ltd. is not merely about establishing a cold storage facility, it is about building a sustainable future for Indian agriculture through innovation, technology and entrepreneurship.

Through their hard work and visionary leadership, Smt. Pallavi Pacharalli and Smt. Satyavani Kuruvalli have demonstrated how modern cold storage infrastructure can transform post-harvest management, generate employment and create lasting economic impact in rural areas. Their journey reflects the transformative power of NHB schemes in empowering entrepreneurs, strengthening horticulture infrastructure and promoting sustainable agricultural growth in India. Their remarkable achievement will continue to inspire future generations to adopt innovation and strive for excellence in the field of agricultural infrastructure and cold storage management.

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# Future Skills for Agricultural Graduates in the Era of Digital Agriculture

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Agriculture remains the backbone of India's economy, ensuring food security, generating employment, and sustaining millions of rural livelihoods. However, the sector is being reshaped by climate change, shrinking natural resources, global competition, and rapid technological advancements. The transition from conventional farming to knowledge-driven, technology-enabled agriculture demands a new generation of professionals equipped with digital, technical, and managerial competencies.

Recognizing this need, the National Education Policy (NEP) 2020 promotes competency-based, multidisciplinary, and skill-oriented education, while the National Agricultural Higher Education Project (NAHEP) has accelerated curriculum reforms, experiential learning, digital infrastructure, and industry linkages in agricultural universities. These initiatives are preparing institutions to meet the evolving demands of the agricultural sector.

The rise of Agriculture 4.0 and 5.0, powered by artificial intelligence (AI), the Internet of Things (IoT), drones, robotics, remote sensing, and big data analytics, is transforming farming into a smart, data-driven enterprise. As a result, employers increasingly seek graduates who combine strong agricultural knowledge with digital literacy, innovation, entrepreneurship, critical thinking, and leadership. Preparing future-ready agricultural graduates is no longer just an educational goal—it is essential for building a resilient, sustainable, and globally competitive agricultural sector.

## Digital Agriculture: The New Reality

Digital agriculture is revolutionizing farming by integrating advanced technologies such as artificial intelligence (AI), the Internet of Things (IoT), drones, Geographic Information Systems (GIS), remote sensing, robotics, blockchain, and big data analytics into agricultural production, extension, and value chains. These innovations are enabling data-driven decision-making, precision farming, smart irrigation, real-time crop monitoring, and digital advisory services, making agriculture more productive, efficient, and climate-resilient.

This technological revolution is also reshaping agricultural careers. The Developing Critical Agriculture Skills Courses in India (DCASCI) project identifies five emerging occupations—Digital Agriculture Extension Promoter, Carbon Farming Practitioner, Livestock Green Management Promoter, Integrated Farming Practitioner, and Organic Farm and Business Promoter—reflecting the growing demand for professionals with digital expertise, sustainability knowledge, and interdisciplinary skills.

India's rapidly expanding agri-tech ecosystem is creating new opportunities in precision agriculture, digital extension, farm data analytics, drone services, climate-smart agriculture, and agribusiness. At the same time, Smart Farmer Producer Organizations (Smart FPOs) are emerging as a transformative model, leveraging digital technologies, market intelligence, and collective marketing to strengthen farmer incomes and value chains.





As agriculture becomes smarter and more technology-driven, the expectations from agricultural graduates are also evolving. Beyond a strong foundation in agricultural sciences, they must develop competencies in AI, data analytics, GIS, drone technology, digital communication, and climate-smart agriculture. By integrating these competencies into curricula through experiential learning, digital laboratories, and industry partnerships, agricultural universities can prepare graduates to lead the transition towards smart, sustainable, and resilient agriculture.

### **Future Skills Every Agricultural Graduate Needs**

The rapid transformation of agriculture has redefined the skills required for tomorrow's professionals. Success in modern agriculture is no longer determined by technical knowledge alone; it also depends on digital competence, innovation, sustainability, entrepreneurship, and the ability to work with people and technology. Recognizing these changing workforce needs, the Developing Critical Agriculture Skills Courses in India (DCASCI) project identified five emerging career pathways—Digital Agriculture Extension Promoter, Carbon Farming Practitioner, Livestock Green Management Promoter, Integrated Farming Practitioner, and Organic Farm and Business Promoter—highlighting the growing demand for multidisciplinary professionals capable of leading agricultural transformation.

#### **1. Digital and Technological Competencies**

Digital literacy has become a core competency for agricultural graduates. Professionals must be comfortable using computers, mobile applications, cloud platforms, and digital databases while also understanding technologies such as artificial intelligence (AI), machine learning, GIS, drones, GPS, IoT, remote sensing, and big data analytics. These tools are driving precision agriculture by improving crop monitoring, disease diagnosis,

weather forecasting, irrigation management, and farm decision-making. The emergence of the Digital Agriculture Extension Promoter reflects the increasing need for professionals who can effectively connect digital technologies with farmers and extension services.

#### **2. Sustainability and Climate-Smart Skills**

Climate change has made sustainable agriculture a necessity rather than a choice. Future graduates should possess knowledge of climate-smart agriculture, integrated farming systems, water conservation, regenerative agriculture, carbon farming, renewable energy, and biodiversity conservation. These competencies will help improve farm productivity while protecting natural resources. Reflecting this shift, the DCASCI project identifies Carbon Farming Practitioner and Livestock Green Management Promoter as emerging green occupations that support environmentally sustainable agricultural development.

#### **3. Entrepreneurial and Business Competencies**

Modern agriculture offers opportunities far beyond crop production. Graduates should understand agribusiness management, value addition, supply chain management, digital marketing, financial planning, and startup development to become job creators rather than job seekers. The emerging roles of Organic Farm and Business Promoter and Integrated Farming Practitioner demonstrate how entrepreneurship, sustainable farming, and business management are becoming central to future agricultural careers.

#### **4. Communication, Leadership, and Professional Skills**

Technology can only create impact when people are able to adopt and use it effectively. Therefore, agricultural graduates must be strong communicators who can translate scientific knowledge into practical





solutions for farmers, policymakers, and agribusinesses. Leadership, teamwork, negotiation, and extension communication skills are equally important for promoting innovation, building partnerships, and managing multidisciplinary projects.

### 5. Critical Thinking, Lifelong Learning, and Ethical Responsibility

Agriculture is evolving rapidly in response to technological advances, climate uncertainty, and changing market demands. Graduates must therefore develop critical thinking, creativity, and evidence-based decision-making skills to solve complex agricultural problems. Continuous learning through professional training, certifications, and digital learning platforms is essential to remain relevant in a dynamic sector. At the same time, the increasing use of AI and digital technologies calls for responsible and ethical practices that ensure data privacy, transparency, inclusiveness, and equitable access to innovation.

### Role of Agricultural Universities in Building Future-Ready Graduates

Agricultural universities are at the forefront of preparing the next generation of professionals for the digital era. As agriculture becomes increasingly technology-driven and market-oriented, universities must move beyond conventional teaching methods and adopt a **competency-based, student-centred approach** that develops technical expertise alongside digital, entrepreneurial, and leadership skills.

Curricula should be regularly updated to reflect emerging areas such as artificial intelligence, precision agriculture, climate-smart farming, agribusiness, and sustainable food systems. Classroom learning should be complemented with **experiential approaches**, including field demonstrations, internships, live projects, digital laboratories, startup incubation, hackathons, and

industry exposure, enabling students to apply knowledge to real-world agricultural challenges.

Faculty members also need continuous professional development to keep pace with rapidly evolving technologies. Regular training in AI, drones, GIS, remote sensing, data analytics, and digital extension tools will help educators deliver relevant and high-quality learning experiences. At the same time, universities should invest in modern digital infrastructure, including smart classrooms, AI-enabled learning platforms, drone laboratories, and precision farming facilities.

Strong collaboration with **ICAR institutes, Krishi Vigyan Kendras (KVKs), Agricultural Skill Councils, agri-tech companies, Farmer Producer Organizations (FPOs), research organizations, and government agencies** can provide students with valuable opportunities for internships, industry mentoring, skill development, and hands-on learning. Aligning curricula with **national occupational standards and industry requirements** will ensure that graduates possess the competencies needed by the evolving agricultural sector.

By embracing innovation, strengthening industry partnerships, and promoting practical, technology-enabled learning, agricultural universities can produce future-ready graduates who are capable of driving digital transformation, sustainable agriculture, and resilient food systems.

### Challenges

Despite significant progress in agricultural education, several challenges continue to limit the development of a workforce equipped for the era of digital agriculture. One of the most pressing concerns is that many curricula still emphasize conventional agricultural practices while providing limited exposure to emerging technologies such as artificial intelligence, precision agriculture, drones, big data analytics, and digital extension services. As a result, graduates often enter the workforce without the



competencies required by the rapidly evolving agricultural sector.

Another major challenge is the shortage of faculty members with expertise in digital agriculture and related technologies. Continuous faculty capacity building is essential to ensure that educators remain updated with technological advancements and can effectively prepare students for future careers.

Limited digital infrastructure further constrains the learning environment in many agricultural institutions. Inadequate access to smart classrooms, high-speed internet, drone laboratories, precision farming equipment, GIS and remote sensing facilities, and AI-enabled learning platforms restricts opportunities for hands-on training and experiential learning.

A persistent gap between academia and industry also affects graduate employability. Weak collaboration among universities, agribusiness companies, agri-tech startups, research organizations, and extension agencies often results in curricula that are insufficiently aligned with current industry requirements. Consequently, students receive limited exposure to real-world agricultural challenges, modern technologies, internships, and workplace practices.

In addition, the digital divide among students, particularly those from rural and economically disadvantaged backgrounds, creates unequal access to digital learning resources and emerging technologies. Differences in digital literacy and internet connectivity can hinder students' ability to fully benefit from technology-enabled education.

Addressing these challenges requires a coordinated effort involving universities, policymakers, industry, research organizations, and development agencies. Investments in modern infrastructure, continuous curriculum revision, faculty development, stronger industry partnerships, and inclusive digital education will be critical to preparing agricultural graduates

who are capable of leading the transformation towards smart, sustainable, and resilient agriculture.

### Way Forward

Preparing graduates for the future of agriculture requires reimagining agricultural education beyond traditional classroom teaching. Universities should adopt a competency-based and learner-centric approach that combines scientific knowledge with digital skills, innovation, entrepreneurship, and sustainability. Interdisciplinary curricula integrating artificial intelligence, data science, agribusiness, environmental sciences, and communication will better equip students for the evolving demands of Agriculture 4.0 and 5.0.

Greater emphasis should be placed on experiential learning through internships, field projects, digital laboratories, innovation hubs, startup incubation, hackathons, and industry immersion, enabling students to apply classroom knowledge to real-world agricultural challenges. Introducing credit-based skill courses in areas such as digital agriculture, precision farming, climate-smart agriculture, drone technology, AI, carbon farming, and agribusiness can further enhance employability and lifelong learning.

Continuous faculty development through Training of Trainers (ToT) programmes is equally important to ensure that educators remain updated with emerging technologies and innovative teaching practices. Stronger collaboration among agricultural universities, ICAR institutes, Krishi Vigyan Kendras (KVKs), Agricultural Skill Councils, agri-tech companies, Farmer Producer Organizations (FPOs), and international institutions can provide students with valuable opportunities for internships, industry mentoring, joint research, and hands-on training. In addition, dual certification programmes that combine academic degrees with industry-recognized professional credentials can improve graduates' career prospects and global competitiveness.



By embracing curriculum innovation, industry collaboration, and competency-based learning, agricultural universities can nurture a new generation of professionals capable of driving digital transformation, sustainable agriculture, and resilient food systems.

## Conclusion

The future of agriculture depends not only on advanced technologies but also on skilled professionals who can apply them effectively. Agricultural graduates must develop digital competence, sustainability awareness, entrepreneurial thinking, and strong leadership and communication skills to meet the evolving needs of the sector. By adopting competency-based education, experiential learning, and stronger industry partnerships, agricultural universities can prepare future-ready graduates who will drive innovation, enhance food security, and contribute to a resilient and sustainable agricultural system.

“The farms of tomorrow will not be transformed by technology alone they will be transformed by skilled, innovative, and future-ready agricultural graduates who can turn knowledge into sustainable solutions for farmers, society, and the planet.”

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# Building Climate-Resilient Agriculture through Effective Extension Strategies

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## Introduction

Climate change poses a major challenge to global efforts toward reducing hunger, malnutrition, poverty, and ensuring sustainable food production. Increasing frequency and intensity of extreme weather events such as droughts, floods, heat waves, and erratic rainfall patterns are adversely affecting agricultural productivity, particularly in rainfed and smallholder farming systems. Climate change influences crop yield and quality, alters input requirements, accelerates soil degradation, and increases risks associated with agricultural production, thereby threatening global food security. The need to increase food production by approximately 70% by 2050 further highlights the urgency of developing climate-resilient agricultural systems.

India has experienced significant climate-related agricultural losses due to cyclones, floods, droughts, and other extreme events. During 2016-2021, natural disasters damaged more than 36 million hectares of cropped area, resulting in substantial economic losses for farming communities. Similarly, recent floods in Punjab caused extensive damage to agricultural land, affecting crop productivity, soil health, and farmers' livelihoods. Climate-induced risks have also contributed to fluctuations in agricultural income, emphasizing the need for effective climate-resilient agriculture (CRA) strategies.

Climate resilience in agriculture requires coordinated efforts among farmers, extension professionals, researchers, policymakers, and other stakeholders. Along with promoting adaptation strategies, reducing

greenhouse gas emissions through sustainable agricultural practices is essential for long-term resilience. Agricultural extension services play a crucial role in this process by facilitating knowledge exchange, promoting climate-smart technologies, strengthening farmers' capacities, and connecting communities with institutional support. Effective extension systems are therefore essential for promoting sustainable and climate-resilient agricultural development.

## Understanding Climate Resilient Agriculture

Climate Resilient Agriculture (CRA) is an integrated approach that aims to enhance agricultural productivity and incomes, strengthen resilience to climate change, and reduce greenhouse gas emissions. It involves modifying farming practices to improve food security, reduce vulnerability, and enable communities to cope with climate-induced stresses such as droughts, hailstorms, and extreme rainfall events. As a component of Climate-Smart Agriculture, CRA emphasizes adaptation, sustainability, and resilience through innovative technologies and sustainable practices. FAO defines CRA as the capacity of agricultural systems to anticipate, adapt to, absorb, and recover from climate impacts while ensuring sustainable livelihoods and environmental protection.

## Role of Agricultural Extension in Climate Resilience

Climate-resilient technologies cannot achieve meaningful impact unless farmers understand, trust, and effectively adopt them. Agricultural extension



serves as a critical link between scientific research and farming communities by facilitating access to climate information, weather-based advisories, improved technologies, and capacity-building opportunities. Over time, the role of extension has evolved from a traditional technology transfer approach toward a broader knowledge facilitation and innovation support system that strengthens farmers' ability to manage climate risks.

Extension systems play a vital role in enhancing adaptive capacity by promoting climate-smart agricultural practices such as efficient water management, stress-tolerant crop varieties, integrated nutrient management, conservation agriculture, and diversified farming systems. Through training programmes, demonstrations, Farmer Field Schools, and participatory approaches, extension enables farmers to understand climate risks, improve decision-making, and adopt context-specific solutions.

Furthermore, extension organizations facilitate collaboration among research institutions, government agencies, private-sector stakeholders, and farming communities to develop and disseminate locally suitable climate-resilient technologies. By integrating scientific knowledge with farmers' indigenous experiences, extension can improve the relevance, acceptance, and sustainability of climate adaptation strategies. Strengthening extension networks, digital advisory services, and inclusive approaches targeting smallholders, women farmers, and youth is essential for building resilient agricultural systems in the face of increasing climate uncertainties.

## **Effective Extension Strategies for Building Climate-Resilient Agriculture**

### **1. Promoting Climate-Smart Agricultural Practices**

Extension agencies should encourage farmers to adopt climate-smart agricultural practices that

improve productivity while conserving natural resources. Important practices include conservation agriculture, zero tillage, direct-seeded rice, integrated nutrient management, crop diversification, agroforestry, and integrated farming systems. For example, in Punjab, technologies such as the Happy Seeder and Direct Seeded Rice (DSR) are helping farmers reduce crop residue burning, conserve water, and improve soil health. Demonstrations and farmer training programmes have played an important role in increasing awareness and adoption of these practices.

### **2. Strengthening Climate Information and Early Warning Services**

Timely climate information is vital for reducing agricultural risks. Through weather forecasts, early warning systems, and digital platforms such as Meghdoot, Damini, mKisan Portal, and Kisan Suvidha App, extension agencies support informed decisions on sowing, irrigation, and crop management, thereby enhancing climate resilience.

### **3. Capacity Building through Training and Demonstrations**

Building farmers' knowledge and skills is vital for climate resilience. Extension organizations enhance adaptive capacity through training, demonstrations, Farmer Field Schools, exposure visits, and participatory learning, enabling informed decisions and adoption of climate-resilient practices. Special focus is needed on women farmers, youth, and smallholders who face greater barriers to resources and information.

### **4. Promoting Soil and Water Conservation**

Healthy soil and efficient water management are essential components of climate-resilient agriculture, as they enhance resource-use efficiency and reduce vulnerability to drought and water scarcity. Extension professionals should promote practices such as rainwater harvesting, farm ponds, watershed





management, mulching, conservation tillage, micro-irrigation, laser land levelling, and soil test-based nutrient management. These approaches improve soil health, conserve water, reduce production costs, and strengthen farmers' adaptive capacity to climate variability.

### **5. Encouraging Crop Diversification and Climate-Resilient Varieties**

Climate variability increases the vulnerability of monocropping systems; therefore, extension services should promote diversified farming systems through climate-resilient crop varieties, pulses, oilseeds, horticultural crops, livestock integration, and agroforestry. Such diversification reduces dependence on a single crop, improves farm income stability, and enhances resilience against climate-related production risks.

### **6. Expanding Digital Agricultural Extension**

Digital technologies are transforming agricultural extension by improving access to timely and location-specific information through mobile applications, remote sensing, artificial intelligence, and online advisory platforms. Digital extension services support farmers with weather advisories, pest and disease management, market information, and capacity-building resources. However, improving digital literacy, infrastructure, and connectivity is crucial to ensure inclusive access and maximize the benefits of digital agriculture.

### **7. Promoting Participatory Learning and Farmer Innovation**

Extension approaches based on experiential learning, such as frontline demonstrations, result demonstrations, climate-smart villages, and farmer-to-farmer learning, enhance farmers' confidence by allowing them to evaluate technologies under local conditions. Integrating farmers' indigenous knowledge with scientific innovations helps develop locally suitable and climate-resilient solutions.

### **8. Strengthening Institutional Linkages**

Climate resilience requires strong multi-stakeholder collaboration among extension agencies, research institutions, agricultural universities, KVKs, FPOs, financial institutions, and government departments. Such partnerships improve farmers' access to climate-smart technologies, credit, insurance, markets, and adaptation programmes, thereby strengthening their adaptive capacity.

### **Challenges Facing Climate Extension Services**

Despite increasing efforts to promote climate-resilient agriculture, several challenges limit the effectiveness of climate extension services. Major constraints include inadequate climate-related knowledge among extension personnel, limited institutional capacity, insufficient financial resources, and weak coordination among research, extension, and policy actors. In many regions, extension systems also struggle to provide location-specific climate advisories due to gaps in climate information generation, interpretation, and dissemination. These limitations reduce farmers' ability to make timely decisions and adopt suitable adaptation practices.

Smallholder farmers face additional barriers, including limited access to credit, insurance, quality inputs, markets, and climate-smart technologies, which restrict their adaptive capacity. Emerging challenges such as the digital divide, low digital literacy, poor connectivity, and unequal access to information platforms further limit the effectiveness of digital extension approaches. Moreover, weak farmer participation and inadequate integration of indigenous knowledge often create gaps between technology development and field-level adoption. Strengthening extension systems through continuous capacity building, participatory approaches, digital inclusion, and stronger research-extension-farmer linkages is essential for enhancing climate resilience.



## Way Forward

Climate change necessitates a paradigm shift in agricultural extension from a technology transfer approach to a climate-responsive, knowledge-driven, and innovation-oriented system. Future extension services should strengthen climate risk management by integrating scientific knowledge with indigenous practices, promoting participatory and demand-driven learning, and fostering stronger collaboration among researchers, extension agencies, policymakers, private organizations, and farming communities. Building the technical capacity of extension professionals and strengthening research-extension-farmer linkages will be critical for delivering timely, location-specific, and evidence-based climate advisory services.

Future extension policies should prioritize digital transformation through artificial intelligence, remote sensing, precision agriculture, climate-smart villages, and decision-support systems to improve the accessibility and effectiveness of climate advisory services. Greater investment in digital infrastructure, institutional capacity, and inclusive extension programmes that actively engage women, youth, Farmer Producer Organizations (FPOs), and local institutions will be essential for scaling climate-smart agriculture. Embedding climate resilience into national agricultural extension policies and strengthening multi-stakeholder innovation platforms will be pivotal for accelerating sustainable agricultural transformation, enhancing farmers' adaptive capacity, and achieving long-term food and nutritional security.

## Conclusion

Climate change has transformed resilience from an agricultural objective into a development imperative. While climate-smart technologies offer practical solutions, their widespread adoption depends on strong, inclusive, and responsive agricultural extension systems. Extension must evolve from a

technology dissemination model to a knowledge and innovation ecosystem that empowers farmers to anticipate, adapt to, and recover from climate risks. Future agricultural policies should place climate-responsive extension at the centre of adaptation strategies by increasing public investment, promoting digital and data-driven advisory services, strengthening institutional partnerships, and ensuring that women, youth, and smallholder farmers remain central to climate resilience initiatives. Such policy commitments will be instrumental in building sustainable, resilient, and food-secure agricultural systems.

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# Artificial Intelligence in Agricultural Extension: Transforming Farming for a Sustainable Future

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## Introduction

Agriculture around the world is under strain. There is tremendous demand to move toward more resilient, equitable, and sustainable food systems because of climate instability, biodiversity loss, land degradation, and ongoing rural poverty. This change is particularly critical in the Global South, where small and marginal farmers face severe structural limitations, unstable livelihoods, restricted access to markets, inputs, and information, and increased susceptibility to economic and environmental shocks.

Agricultural extension has traditionally served as the vital link between agricultural research institutions and farming communities by facilitating the transfer of knowledge, technologies, and innovations. Through demonstrations, farmer field schools, training programmes, and participatory learning approaches, extension professionals have significantly contributed to enhancing agricultural productivity, improving livelihoods, and promoting sustainable farming practices. However, conventional extension systems in many developing countries are increasingly constrained by inadequate manpower, limited financial resources, weak infrastructure, and an ever-growing demand for location-specific, timely, and personalized advisory services. The widening farmer-to-extension worker ratio further limits the effectiveness of traditional extension approaches, particularly in remote and resource-poor regions.

The rapid advancement of digital technologies has opened new opportunities to strengthen agricultural

extension systems. The widespread availability of smartphones, affordable internet connectivity, remote sensing, satellite imagery, drones, Internet of Things (IoT) devices, and cloud computing has transformed the way agricultural information is generated and disseminated. These technologies enable the collection of real-time data on weather, soil conditions, crop health, pest outbreaks, and market trends. Nevertheless, the enormous volume of agricultural data requires intelligent analytical systems capable of converting complex information into practical, farmer-friendly recommendations that can support informed decision-making.

Artificial Intelligence (AI) has emerged as one of the most transformative technologies capable of addressing these challenges. AI integrates machine learning, computer vision, natural language processing, predictive analytics, and generative AI to analyze large datasets, identify patterns, and generate actionable insights. Within agricultural extension, AI-powered systems are increasingly being used to diagnose crop diseases through image recognition, recommend fertilizers based on soil characteristics, optimize irrigation schedules, forecast weather-related risks, provide market intelligence, and deliver multilingual advisory services through conversational agents. Rather than replacing extension professionals, AI is expected to complement their expertise by enabling faster, more accurate, and personalized advisory services that can reach millions of farmers simultaneously.



## AI in Agricultural Extension

AI includes machine learning, computer vision, natural language processing and generative AI. These technologies support crop management, nutrient recommendations, pest diagnosis, irrigation scheduling, weather interpretation and market intelligence. Rather than replacing extension workers, AI augments their capacity to reach more farmers efficiently.

The integration of AI into agricultural extension represents a paradigm shift from generalized information dissemination to intelligent, demand-driven, and context-specific advisory services. AI-powered digital platforms can continuously learn from historical data, local farming conditions, and farmer feedback to generate customized recommendations tailored to individual farm situations. Combined with participatory extension approaches and human expertise, AI has the potential to strengthen resilience against climate change, improve resource-use efficiency, enhance productivity, and contribute significantly to achieving sustainable and inclusive food systems. As governments, research organizations, startups, and extension agencies increasingly invest in digital agriculture, AI is poised to become an indispensable partner in shaping the future of agricultural extension. AI-driven chatbots and virtual assistants provide round-the-clock advisory services, answering farmers' queries in real time through text or voice in multiple languages, thereby extending the reach of extension services to remote and underserved areas. Machine learning algorithms can identify disease symptoms and nutrient deficiencies from images captured by smartphones or drones, enabling early detection and timely intervention.

## Applications of AI in Agricultural Extension

Artificial intelligence (AI) has significantly enhanced agricultural extension by enabling intelligent decision support systems (DSS) that provide

personalized recommendations based on soil characteristics, weather conditions, crop growth stages, and farm management practices. These systems improve decision-making, increase resource-use efficiency, and reduce production risks, thereby strengthening sustainable agricultural development.

**AI-Based Crop Disease and Pest Diagnosis:** Machine learning and deep learning algorithms have revolutionized crop health management by accurately detecting diseases, insect pests, and nutrient deficiencies from digital images captured through smartphones, drones, and field sensors. AI-assisted diagnosis enables extension professionals to provide rapid advisory services, reducing crop losses and minimizing unnecessary pesticide applications. Image recognition techniques based on convolutional neural networks (CNNs) have demonstrated high diagnostic accuracy across several crops.

AI supports precision agriculture using drones, sensors, satellites and IoT. Smartphone applications diagnose diseases from images, recommend fertilizers, forecast weather risks, optimize irrigation and connect farmers with markets. Voice-enabled systems in regional languages improve accessibility for smallholders.

## Benefits of AI:

Artificial Intelligence (AI) offers numerous benefits to agricultural extension by making advisory services more efficient, accessible, and responsive to farmers' needs. One of its most significant advantages is the availability of 24×7 advisory support, enabling farmers to receive instant guidance on crop management, pest and disease control, irrigation, fertilization, and market trends at any time. AI-powered systems analyze data from soil conditions, weather forecasts, crop health, and historical records to provide personalized recommendations tailored to individual farms, leading to more accurate and effective decision-making. Rapid decision support





allows farmers to respond quickly to changing environmental conditions, pest outbreaks, and extreme weather events, thereby reducing production risks and minimizing losses. AI also supports multilingual communication through chatbots and voice assistants, allowing farmers to access information in their local languages and making extension services more inclusive and user-friendly. Furthermore, AI enhances resource-use efficiency by optimizing the application of water, fertilizers, pesticides, and other inputs, which reduces production costs while promoting environmental sustainability. By integrating climate forecasting and predictive analytics, AI strengthens farmers' climate resilience, enabling them to adopt suitable adaptation strategies and improve long-term productivity. Additionally, AI fosters stronger linkages between farmers, researchers, extension professionals, and markets by facilitating real-time information exchange, technology dissemination, market intelligence, and knowledge sharing. These benefits collectively contribute to increased agricultural productivity, improved farm profitability, enhanced food security, and sustainable agricultural development.

### Challenges

Despite its significant potential, the adoption of Artificial Intelligence (AI) in agricultural extension faces several important challenges. One of the primary challenge is the limited digital literacy among many farmers, particularly in rural areas, which makes it difficult for them to effectively use AI-powered tools and digital platforms. Inadequate internet connectivity and limited access to digital infrastructure further restrict the implementation of AI technologies in remote regions. Data privacy and security are also major concerns, as AI systems often rely on collecting and processing large volumes of personal and farm-related information, raising questions about data ownership, consent, and protection from misuse. Another challenge is algorithmic bias, where AI models trained on

incomplete or unrepresentative datasets may produce recommendations that are unsuitable for certain regions, crops, or farming communities. In addition, AI systems can sometimes generate inaccurate or misleading responses due to outdated information, incorrect data inputs, or limitations in the underlying models, potentially leading to poor farming decisions if used without verification. The effectiveness of AI also depends on the availability of reliable, high-quality, and locally relevant datasets that reflect regional climatic conditions, soil characteristics, crop varieties, pest and disease patterns, and local farming practices. Developing and maintaining such datasets requires substantial investment, collaboration, and continuous updating. Therefore, while AI can greatly enhance agricultural extension services by providing timely and data-driven recommendations, human oversight remains essential. Agricultural experts, extension workers, and researchers must validate AI-generated advice, interpret recommendations within the local context, and ensure that farmers receive accurate, practical, and trustworthy guidance. A balanced approach that combines AI capabilities with human expertise is crucial for achieving sustainable and inclusive agricultural development.

### Conclusion

Artificial Intelligence is transforming agricultural extension from a conventional information delivery system into a data-driven, farmer-centric, and knowledge-intensive service capable of providing timely, personalized, and location-specific advisories. By integrating technologies such as machine learning, computer vision, natural language processing, remote sensing, and IoT, AI enhances decision-making in areas such as crop management, disease diagnosis, precision farming, weather forecasting, irrigation, and market intelligence, thereby improving productivity, resource-use efficiency, and climate resilience. However, the successful integration of AI into extension systems depends on addressing challenges related to digital infrastructure, digital literacy, data quality, privacy,



algorithmic bias, and equitable access, particularly for smallholder farmers. Rather than replacing extension professionals, AI should be viewed as a complementary tool that strengthens their capacity to deliver more efficient, inclusive, and evidence-based advisory services. With appropriate investments in technology, institutional support, and capacity building, AI has the potential to play a pivotal role in advancing sustainable agriculture, enhancing rural livelihoods, and contributing to global food security and the achievement of the Sustainable Development Goals.

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# Urolithin A: A Promising Postbiotic for Healthy Aging

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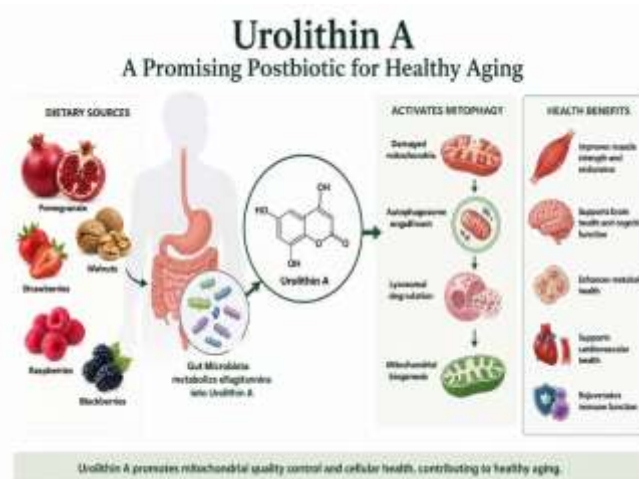
Aging is a complex biological process characterized by the progressive decline in physiological function, increased susceptibility to chronic diseases, and reduced regenerative capacity. While chronological aging is inevitable, biological aging can be influenced by environmental factors, dietary habits, physical activity, and the composition of the gut microbiome (D'Amico *et al.*, 2021; Piva *et al.*, 2023). Recent advances in geroscience (biological mechanisms of aging) have identified mitochondrial dysfunction as one of the principal hallmarks of aging, emphasizing the importance of maintaining mitochondrial quality for healthy longevity.

Among the emerging bioactive compounds targeting mitochondrial health, Urolithin A (UA) has attracted considerable scientific interest. Unlike many commercially available anti-aging supplements with limited clinical evidence, Urolithin A has demonstrated efficacy in preclinical studies and randomized controlled clinical trials by activating mitophagy, the selective autophagic removal of dysfunctional mitochondria. Enhancement of mitophagy improves mitochondrial turnover, ATP production, and cellular homeostasis, thereby promoting healthy aging (D'Amico *et al.*, 2021; Singh *et al.*, 2022).

## Urolithin A: A Microbiome-Derived Postbiotic

Urolithin A is a naturally occurring postbiotic metabolite that is not directly present in foods but is generated through microbial metabolism of dietary ellagitannins and ellagic acid in the human intestine. Ellagitannins are abundant in foods such as pomegranate, walnuts, pecans, strawberries,

raspberries, and blackberries. Following ingestion, gut microorganisms convert ellagitannins into ellagic acid, which is subsequently transformed into Urolithin A as illustrated in Figure 1. (D'Amico *et al.*, 2021; Piva *et al.*, 2023).



However, the capacity to produce Urolithin A varies considerably among individuals because of differences in gut microbial composition. Studies have reported that only approximately 30-50% of healthy adults possess the microbial species required for efficient Urolithin A production. Consequently, individuals consuming identical diets may exhibit markedly different physiological responses, highlighting the importance of personalized nutrition and gut microbiome diversity (Piva *et al.*, 2023; D'Amico *et al.*, 2021).

## Cellular Aging and Mitochondrial Dysfunction

Mitochondria are essential organelles responsible for ATP synthesis through oxidative phosphorylation and are therefore regarded as the energy-producing centers of the cell. Aging is associated with progressive mitochondrial DNA mutations, impaired



oxidative phosphorylation, increased production of reactive oxygen species (ROS), reduced ATP generation, and chronic low-grade inflammation (Leduc-Gaudet *et al.*, 2021; Liu *et al.*, 2023).

Under physiological conditions, damaged mitochondria are continuously eliminated through mitophagy, a highly regulated quality-control mechanism that maintains mitochondrial integrity. However, mitophagy efficiency declines with age, resulting in the accumulation of dysfunctional mitochondria that further exacerbate oxidative stress and contribute to sarcopenia, neurodegenerative disorders, metabolic diseases, cardiovascular dysfunction, and immune senescence (Liu *et al.*, 2023; Leduc-Gaudet *et al.*, 2021).

### Urolithin A as a Natural Mitophagy Activator

Among naturally occurring compounds, Urolithin A is recognized as one of the most potent activators of mitophagy. It promotes the selective removal of damaged mitochondria through autophagic pathways, thereby stimulating mitochondrial biogenesis and restoring mitochondrial function (D'Amico *et al.*, 2021; Faitg *et al.*, 2024).

The mechanism involves identification of dysfunctional mitochondria, encapsulation within autophagosomes, lysosomal degradation, and subsequent generation of new mitochondria. This coordinated process enhances ATP production, improves oxidative metabolism, increases muscle endurance, and restores cellular resilience. Unlike conventional antioxidant supplements that merely scavenge reactive oxygen species, Urolithin A targets the fundamental cause of mitochondrial deterioration by improving mitochondrial quality control (Faitg *et al.*, 2024; Liu *et al.*, 2023).

### Animal Studies

Preclinical studies have provided compelling evidence supporting the biological activity of Urolithin A (UA) in promoting healthy aging through

mitochondrial quality control. Initial investigations utilizing the nematode *Caenorhabditis elegans*, a well-established model organism in aging research, demonstrated that UA supplementation significantly extended lifespan while improving locomotor activity, muscle function, and mitochondrial efficiency. These findings established mitophagy activation as a critical mechanism underlying the longevity-promoting effects of UA (D'Amico *et al.*, 2021; Piva *et al.*, 2023).

Subsequent studies conducted in aged murine models further validated these observations. Dietary administration of UA enhanced skeletal muscle endurance, increased exercise capacity, improved mitochondrial respiration, and reduced systemic inflammatory responses. Moreover, experimental models of neurodegenerative diseases demonstrated improvements in cognitive performance and neuronal mitochondrial function following UA supplementation. Additional investigations have suggested potential therapeutic benefits in obesity, non-alcoholic fatty liver disease, Parkinson's disease, Alzheimer's disease, and cardiovascular dysfunction, emphasizing the broad physiological significance of restoring mitochondrial homeostasis (Faitg *et al.*, 2024; Fang *et al.*, 2019; Piva *et al.*, 2023).

### Human Clinical Evidence

The translation of preclinical findings into human studies has substantially strengthened the scientific credibility of Urolithin A as a nutritional intervention for healthy aging. Several randomized, double-blind, placebo-controlled clinical trials have evaluated its safety, bioavailability, and physiological efficacy in older adults (Singh *et al.*, 2022; D'Amico *et al.*, 2021).

In one of the earliest clinical investigations involving healthy adults aged 61–85 years, participants received either placebo, 500 mg/day, or 1000 mg/day of UA for four weeks. The intervention was well tolerated without serious adverse events,



demonstrating excellent safety and predictable pharmacokinetic characteristics. Importantly, skeletal muscle biopsies revealed significant upregulation of genes associated with mitochondrial function and mitophagy, providing molecular evidence that UA effectively activates mitochondrial quality-control pathways in humans (D'Amico *et al.*, 2021; Singh *et al.*, 2022).

A subsequent randomized clinical trial involving older adults reported that prolonged UA supplementation significantly improved muscle endurance, enhanced ATP production, increased biomarkers of mitochondrial health, and improved six-minute walking performance and muscle strength. These outcomes suggest that improved mitochondrial function can translate into clinically meaningful improvements in physical performance and mobility among aging populations (Singh *et al.*, 2022; Faitg *et al.*, 2024).

### **Urolithin A and Immune Aging**

Age-associated decline in immune function, commonly referred to as immunosenescence, contributes to increased susceptibility to infections, chronic inflammation, and impaired vaccine responsiveness. Emerging evidence indicates that mitochondrial dysfunction plays a central role in immune cell exhaustion, particularly within T lymphocytes (Denk *et al.*, 2025; Liu *et al.*, 2023).

Recent placebo-controlled clinical investigations have demonstrated that UA supplementation enhances mitochondrial metabolism in immune cells, restores mitochondrial fitness, and promotes expansion of less-exhausted T-cell populations. Additionally, reductions in biomarkers associated with immune aging have been observed following supplementation, suggesting that activation of mitophagy may improve immune resilience in older adults. Although these findings are highly promising, longer-duration clinical trials involving larger and more diverse populations are required before

definitive conclusions regarding immune health benefits can be established (Denk *et al.*, 2025; D'Amico *et al.*, 2021).

### **Potential Health Benefits of Urolithin A**

#### **Healthy Muscle Aging**

Loss of skeletal muscle mass and function (sarcopenia) represents one of the earliest manifestations of biological aging. Clinical evidence indicates that UA supplementation improves muscle endurance, reduces fatigue, enhances exercise performance, and accelerates post-exercise recovery by improving mitochondrial efficiency. Consequently, UA has emerged as a promising nutritional strategy for preserving physical function and independence in older adults (Singh *et al.*, 2022; Faitg *et al.*, 2024).

#### **Brain Health**

Neuronal cells exhibit exceptionally high energy requirements, making them particularly vulnerable to mitochondrial dysfunction. Experimental studies have demonstrated that UA enhances mitophagy within neurons, thereby reducing oxidative stress and improving mitochondrial function. Animal models of Alzheimer's disease have reported reductions in amyloid- $\beta$  accumulation and tau pathology following mitophagy activation, suggesting that UA may possess neuroprotective potential against age-related neurodegenerative disorders (Fang *et al.*, 2019; Liu *et al.*, 2023).

#### **Metabolic Health**

Mitochondria play a central role in glucose utilization, fatty acid oxidation, and insulin sensitivity. Preclinical investigations indicate that UA enhances mitochondrial metabolic efficiency while reducing inflammatory pathways associated with obesity, insulin resistance, and metabolic syndrome. These findings suggest that UA may contribute to improved metabolic health, although





additional human intervention studies remain necessary (Piva *et al.*, 2023; D'Amico *et al.*, 2021).

### Cardiovascular Health

Oxidative stress and mitochondrial dysfunction contribute significantly to vascular aging and cardiovascular disease progression. Experimental evidence suggests that UA preserves mitochondrial integrity within vascular tissues, thereby reducing oxidative damage and improving endothelial function. These mechanisms indicate potential cardioprotective effects, although robust clinical evidence is still evolving (Leduc-Gaudet *et al.*, 2021; Piva *et al.*, 2023).

### Conclusion

Urolithin A represents one of the most promising microbiome-derived postbiotic compounds currently investigated for promoting healthy aging. Produced through microbial metabolism of dietary ellagitannins, UA activates mitophagy, thereby facilitating the removal of dysfunctional mitochondria and enhancing mitochondrial biogenesis, energy metabolism, and cellular resilience. Evidence from mechanistic studies, animal models, and randomized clinical trials consistently demonstrates beneficial effects on mitochondrial function, skeletal muscle performance, and immune health, with emerging evidence supporting potential roles in neuroprotection, metabolic regulation, and cardiovascular function. Urolithin A illustrates a paradigm shift in aging research by demonstrating that mitochondrial quality control is a modifiable biological target. Continued investigation of this postbiotic may contribute substantially to the development of precision nutrition strategies aimed at extending health span and improving quality of life in aging populations.

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# Forest Bathing and Phytoncides: The Science Behind Why Trees Make Us Healthier

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For most of human history, daily life unfolded under a forest canopy, beside a river or within reach of open soil. That relationship has thinned considerably in the last two generations. More than half of the global population now lives in cities and the figure continues to climb each year, bringing with it rising rates of chronic stress, sleep disruption, hypertension and lifestyle-related disease. Against this backdrop, researchers across immunology, public health and environmental psychology have turned their attention back to a simple, low-cost intervention *viz.* spending unhurried time among trees. In Japan, this practice was formalised in 1982 under the name “Shinrin-Yoku” or forest bathing, coined by the country's Forestry Agency as a public health strategy. Unlike hiking or exercise, forest bathing has no fixed pace or distance target; it asks a person to slow down and absorb the forest through sight, sound, smell, touch and, cautiously, taste. What began as a cultural wellness practice has since accumulated a substantial body of peer-reviewed evidence linking forest exposure to measurable physiological change, much of it centred on a class of airborne plant compounds called phytoncides.

## What Are Phytoncides

Phytoncides are volatile organic compounds that trees and other plants release into the surrounding air, largely as a defence mechanism against insects, fungi and bacteria. Coniferous species such as pine, cedar and cypress are particularly rich sources, releasing monoterpenes including alpha-pinene, beta-pinene, d-limonene and camphene in measurable concentrations within forest air. These compounds were first studied for their antimicrobial role in

protecting the tree itself, but subsequent research found that humans walking among trees inhale them in quantities sufficient to produce systemic effects. Because concentrations of these biogenic volatile organic compounds vary with tree species, canopy density, season and time of day, forest air is not uniform; a dense conifer stand in early morning delivers a very different chemical exposure than a sparse deciduous grove at noon. This variability is part of why researchers increasingly treat forest bathing not as one intervention but as a family of exposures whose intensity depends on where, when and how long a person stays under the canopy.

## Immune System Effects

The most widely cited physiological finding in forest bathing research concerns natural killer or NK cells, a class of white blood cells that form part of the body's first line of defence against virally infected and tumour cells. Early controlled studies found that a two- to three-day forest trip increased both the number and activity of NK cells, an effect that persisted for over a week following exposure and correlated with airborne phytoncide concentration during the trip (Li et al., 2006). Mechanistic work has since traced this effect to increased expression of intracellular cytotoxic proteins such as perforin, granulysin and granzymes inside NK cells following phytoncide inhalation. Anti-inflammatory effects have also been documented at the tissue level *i.e.* phytoncide exposure has been shown to reduce inflammatory markers in animal models of gastrointestinal inflammation, suggesting the compounds act on immune pathways beyond NK cell cytotoxicity alone (Memon et al., 2021). Reviews



synthesising this body of work describe a consistent pattern across studies conducted in Japan, China and more recently Europe and North America: short forest visits reliably shift immune parameters toward a more active, better-regulated state, even though the precise dose-response relationship remains an active area of investigation.

### **Stress Hormones and Cardiovascular Health**

Alongside immune changes, forest exposure consistently lowers physiological stress markers. A systematic review and meta-analysis pooling eight controlled studies found that salivary and serum cortisol, the primary stress hormone, fell significantly after forest exposure in nearly all included trials when compared with urban or indoor control conditions (Antonelli et al., 2019). A more recent physiological study of stressed adults recorded parallel reductions in electrodermal activity alongside increased heart rate variability, both markers of a shift from sympathetic arousal toward parasympathetic, rest-and-recover nervous system activity, following a two-day forest immersion (Queirolo et al., 2024). These autonomic and endocrine shifts translate into measurable cardiovascular benefit. A meta-analysis focused on urban residents found that forest therapy produced significant reductions in both systolic and diastolic blood pressure alongside lowered salivary cortisol relative to matched urban controls (Qiu et al., 2022), and controlled trials in older adults with diagnosed hypertension have reported comparable falls in blood pressure after multi-day forest stays. Taken together, this evidence positions regular forest contact as a plausible, low-risk complement to conventional strategies for managing stress-related cardiovascular risk, though researchers are careful to note that effect sizes vary with exposure duration, forest type and baseline health status.

### **Mental Health and Cognitive Restoration**

The psychological case for forest bathing rests on two influential frameworks that predate the biochemical research by decades. Attention Restoration Theory proposes that natural environments, rich in what the theory terms soft fascination, allow the brain's directed-attention systems to recover from the fatigue induced by constant urban stimulation (Kaplan, 1995). The biophilia hypothesis, meanwhile, argues that humans carry an innate, evolutionarily rooted affinity for living systems, so that contact with vegetation and wildlife satisfies a psychological need rather than merely providing pleasant scenery (Wilson, 1984). Field experiments conducted across dozens of Japanese forest sites lent early empirical weight to these ideas, documenting reduced anxiety, hostility and depression scores alongside physiological calm following brief forest walks (Park et al., 2010). More recent systematic reviews and meta-analyses covering both mental health outcomes and nature therapy more broadly report consistent, moderate effect sizes for reductions in anxiety, depressive symptoms and perceived stress, along with improved sleep quality and mood, across a growing number of randomised and quasi-experimental trials (Kotera et al., 2022; Chen et al., 2025). These reviews also flag genuine limitations worth stating plainly: sample sizes in individual trials remain modest, control conditions vary widely and few studies have followed participants beyond a few weeks, so claims about long-term or preventive benefit should be treated as promising rather than settled.

### **Cognitive Function and Healthy Ageing**

A newer strand of research has moved beyond mood and stress to ask whether forest exposure can support cognitive performance, particularly among older adults facing age-related decline. A within-subjects study tracking elderly participants through a self-guided forest bathing programme found significant improvements in attention, working memory and



creativity following repeated forest visits, measured through standard neuropsychological tools including the Stroop test, the digit span task and the remote associates test (Ramanpong et al., 2025). Notably, the frequency of forest visits over the course of a week correlated more strongly with cognitive gains than the distance walked or the total time spent in any single session, suggesting that regular, shorter exposures may matter more than occasional long ones. This finding echoes Attention Restoration Theory's original premise that natural settings replenish directed attention through gentle, involuntary engagement rather than effortful concentration (Kaplan, 1995), and it extends the theory's relevance from healthy young adults, where most of the foundational research was conducted, to an ageing population for whom cognitive decline carries significant public health and caregiving cost. For a state with a growing elderly population and abundant accessible forest land, this line of evidence suggests that structured, community-level forest walking programmes could serve a preventive role alongside their better-known benefits for stress and cardiovascular health.

### **Limitations and the Need for Further Research**

It would be misleading to present this evidence as settled science. Most forest bathing trials remain small, often enrolling fewer than fifty participants, and a large share rely on healthy young volunteers recruited from universities rather than the older or chronically ill populations who might benefit most. Control conditions also vary considerably between studies, with some comparing forest exposure against a city street and others against an indoor waiting room, which makes it difficult to isolate exactly which sensory or chemical element of the forest environment drives the observed effect. Reviewers of this literature consistently call for larger randomised trials with standardised exposure protocols, longer follow-up periods extending beyond a few weeks and clearer reporting of forest type, season and phytoncide concentration during each intervention.

There is also a marked geographic imbalance in the existing evidence base: the great majority of published trials originate in Japan, China, South Korea and, increasingly, Europe and North America, while temperate and subtropical broadleaf forests, tropical forests and Himalayan conifer forests remain comparatively understudied. Since phytoncide composition differs by tree species, a finding established in a Japanese cypress forest cannot simply be assumed to transfer to a deodar or blue pine forest in Himachal Pradesh, India without local verification.

### **Relevance for the Himalayan Region and Rural India**

For Himalayan states of India, where forest cover extends across a large share of the landscape and villages sit within walking distance of pine, deodar and oak stands, this research carries practical weight beyond academic interest. India's Himalayan states are already emerging as a focus for nature-based tourism and conservation policy, with government forest departments and international conservation bodies documenting a rising number of nature-based initiatives that combine biodiversity protection with community livelihoods and visitor wellbeing. In Himachal Pradesh, a Himalayan state in India, the state forest department has been expanding eco-tourism sites in districts such as Kullu, developing forest-based destinations under controlled, low-impact tourism models that create local employment while keeping ecological disturbance to a minimum. Elsewhere in the Indian Himalayan Region, conservation bodies have called for the systematic documentation of nature-based solutions that combine biodiversity protection with community resilience and human wellbeing, a framing that fits comfortably alongside forest bathing research. Structured forest-based wellness programmes, walking trails through managed forest patches, and sensory-based nature activities have already begun appearing in hill states as a form of health tourism, offering rural communities an additional income





stream built around an asset they already possess rather than one that requires new land conversion. For extension education and rural development practitioners, this opens a genuine convergence point between forestry management, public health messaging and livelihood diversification: guided forest walks, community nature camps and school-based outdoor learning programmes could be positioned not as recreational add-ons but as evidence-informed, low-cost interventions for stress-related illness in both rural and neighbouring urban populations. District-level Krishi Vigyan Kendras and Central and State agriculture Universities, with their existing extension networks and proximity to forest land, are reasonably well placed to pilot such programmes and generate the local data needed to test whether these benefits hold in Himalayan conditions. Realising this potential responsibly will, however, require locally generated data, since almost all the physiological evidence summarised above comes from temperate forests in Japan, China, Europe and North America, and Himalayan conifer and broadleaf stands may release a different phytoncide profile altogether.

## Conclusion

The evidence accumulated over the past two decades makes a credible, if still developing, scientific case for what many cultures have long treated as common sense: sustained time among trees changes how the human body functions, from immune cell activity and stress hormone levels to blood pressure and mood. Phytoncides, the airborne compounds trees release for their own defence, appear to be a meaningful part of that mechanism, alongside the sensory and psychological restoration that natural settings provide more broadly. None of this is presented in the literature as a substitute for medical care, and researchers are consistent in calling for larger, longer and more geographically diverse trials before firm dosage or frequency recommendations can be made. What the research does support is a modest, actionable conclusion: unhurried time in a

forest is not merely pleasant but measurably beneficial, and regions rich in forest cover, including the Himalayan hill states, are well positioned to turn that finding into public health practice, conservation incentive and rural livelihood opportunity at the same time.

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# Carbon sequestration

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Carbon sequestration is the process of capturing atmospheric carbon dioxide (CO<sub>2</sub>) and storing it in natural or artificial reservoirs for extended periods to reduce greenhouse gas concentrations and mitigate climate change (IPCC, 2022). Rapid increases in atmospheric CO<sub>2</sub> resulting from fossil fuel combustion, deforestation, land-use changes, and intensive agricultural activities have accelerated global warming, leading to adverse impacts on ecosystems, biodiversity, food security, water resources, and human well-being. Therefore, enhancing carbon sequestration has become an essential strategy for reducing greenhouse gas emissions and improving environmental sustainability.

Natural ecosystems, including forests, grasslands, wetlands, oceans, and agricultural soils, act as major carbon sinks by absorbing atmospheric CO<sub>2</sub> through photosynthesis and storing it in vegetation, biomass, and soil organic matter (Lal, 2018).

Agricultural soils constitute one of the most important terrestrial carbon reservoirs, containing a greater quantity of carbon than that stored in the atmosphere and living vegetation combined. Their capacity to retain and stabilize carbon can be substantially increased through the adoption of sustainable land management practices, including conservation tillage, crop residue retention, cover cropping, agroforestry, integrated nutrient management, and biochar incorporation. These practices promote the accumulation of soil organic carbon (SOC), improve soil structural stability, increase water retention, enhance nutrient availability and cycling, and ultimately support

sustained agricultural productivity (Minasny et al., 2017; FAO, 2022). By increasing the storage of carbon within terrestrial ecosystems, carbon sequestration contributes to reducing atmospheric greenhouse gas concentrations, rehabilitating degraded landscapes, strengthening resilience to climatic fluctuations, and advancing sustainable agricultural development.

## Terminologies Related to Carbon Sequestration

**Carbon Sink:** A natural or human-managed reservoir that removes and retains more carbon from the atmosphere than it emits over a specified period. Forests, agricultural soils, wetlands, and oceans are among the principal carbon sinks because they continuously capture atmospheric carbon and store it in biomass, organic matter, or sediments.

**Carbon Source:** Any natural process, anthropogenic activity, or environmental reservoir that releases carbon dioxide or other carbon-containing gases into the atmosphere at a rate exceeding its capacity for carbon uptake. Examples include fossil fuel combustion, deforestation, biomass burning, and intensive land-use change.

**Soil Organic Carbon (SOC):** The fraction of carbon contained within soil organic matter, originating from decomposed plant residues, root biomass, microorganisms, animal residues, and other organic inputs. Soil organic carbon is a key indicator of soil quality because it regulates nutrient availability, soil structure, water retention, and biological activity.

**Carbon Stock:** The total amount of carbon accumulated within a defined ecosystem component,



such as soil, vegetation, litter, or biomass, at a particular point in time. Carbon stocks are commonly quantified on an area basis and expressed as megagrams of carbon per hectare ( $\text{Mg C ha}^{-1}$ ) or tonnes of carbon per hectare ( $\text{t C ha}^{-1}$ ).

**Carbon Pool:** A reservoir where carbon is stored and exchanged within the carbon cycle, including atmospheric, terrestrial, oceanic, and geological pools.

**Carbon Flux:** The rate at which carbon moves between different carbon pools, commonly expressed as  $\text{g C m}^{-2} \text{ yr}^{-1}$  or  $\text{Mg C ha}^{-1} \text{ yr}^{-1}$ .

**Carbon Footprint:** The total greenhouse gas emissions caused directly and indirectly by an individual, product, organization, or activity, expressed as  $\text{CO}_2$  equivalent ( $\text{CO}_2\text{e}$ ).

**Carbon Neutrality:** Achieving a balance between greenhouse gas emissions produced and emissions removed or offset.

**Carbon Credit:** A tradable certificate representing the reduction or removal of one metric tonne of carbon dioxide equivalent ( $1 \text{ t CO}_2\text{e}$ ).

**Carbon Farming:** Agricultural practices designed to increase carbon storage in vegetation and soils while reducing greenhouse gas emissions.

**Climate-Smart Agriculture (CSA):** Agricultural practices that sustainably increase productivity, enhance resilience to climate change, and reduce or remove greenhouse gas emissions.

**Climate change mitigation:** A human intervention to reduce emissions or enhance the sinks of greenhouse gases” (IPCC, 2018).

### Types of Carbon sequestration

#### a) Terrestrial Carbon Sequestration

Terrestrial carbon sequestration refers to the capture and long-term storage of atmospheric  $\text{CO}_2$  in

vegetation, forests, grasslands, agricultural lands, and soils through photosynthesis and the accumulation of organic matter (Lal, 2018).

#### b) Soil Carbon Sequestration

Soil carbon sequestration is the process of storing atmospheric carbon as soil organic carbon (SOC) through sustainable land management practices such as conservation tillage, cover cropping, residue retention, and organic amendments (Minasny et al., 2017).

#### c) Forest Carbon Sequestration

Forest carbon sequestration involves the uptake of atmospheric  $\text{CO}_2$  by trees and its storage in aboveground biomass, belowground biomass, litter, deadwood, and forest soils, making forests one of the largest terrestrial carbon sinks (Pan et al., 2011).

#### d) Agricultural Carbon Sequestration

Agricultural carbon sequestration enhances carbon storage in croplands through improved farming practices such as conservation agriculture, crop rotation, agroforestry, and integrated nutrient management (Lal, 2020).

#### e) Blue Carbon Sequestration

Blue carbon sequestration refers to the storage of carbon in coastal and marine ecosystems such as mangroves, salt marshes, and seagrass meadows, which sequester carbon efficiently in both biomass and sediments (Macreadie et al., 2021).

#### f) Geological Carbon Sequestration

Geological carbon sequestration involves capturing carbon dioxide from industrial sources and injecting it into deep underground geological formations such as saline aquifers and depleted oil and gas reservoirs for long-term storage (IPCC, 2018).



**g) Ocean Carbon Sequestration**

Ocean carbon sequestration occurs naturally through the absorption of atmospheric CO<sub>2</sub> by seawater and biological processes involving marine organisms, making the oceans the largest active carbon reservoir on Earth (Friedlingstein et al., 2023).

**h) Mineral Carbon Sequestration**

Mineral carbon sequestration permanently stores CO<sub>2</sub> by converting it into stable carbonate minerals through natural weathering or engineered mineral carbonation processes (Matter et al., 2016).

**i) Engineered (Technological) Carbon Sequestration**

Engineered carbon sequestration includes technologies such as Carbon Capture and Storage (CCS), Carbon Capture, Utilization and Storage (CCUS), and Direct Air Capture (DAC), which remove CO<sub>2</sub> from industrial emissions or directly from the atmosphere for long-term storage or utilization (IEA, 2020).

**j) Biochar Carbon Sequestration**

Biochar carbon sequestration involves converting biomass into a stable, carbon-rich material (biochar) through pyrolysis and incorporating it into soil, where it can remain stable for hundreds to thousands of years while improving soil properties (Lehmann & Joseph, 2015).

**Need of Carbon sequestration to mitigate global warming**

Carbon sequestration has become a critical strategy for mitigating climate change by reducing the concentration of atmospheric carbon dioxide (CO<sub>2</sub>), the primary greenhouse gas responsible for global warming (IPCC, 2018). Terrestrial ecosystems, including agricultural lands, forests, grasslands, and wetlands, function as major carbon sinks by removing atmospheric carbon dioxide through

photosynthetic activity and storing it within plant biomass and soil organic matter (Lal, 2018). Among these ecosystems, agricultural soils possess considerable potential for long-term carbon storage when managed using sustainable practices. Increasing soil organic carbon (SOC) not only contributes to climate change mitigation by reducing atmospheric carbon dioxide concentrations but also improves several key soil functions. Higher SOC levels enhance soil fertility, improve aggregate stability and water retention, stimulate nutrient cycling, and support diverse soil biota, thereby promoting resilient and sustainable agricultural production systems (Minasny et al., 2017). In addition to its environmental benefits, carbon accumulation in agricultural landscapes offers economic opportunities through carbon trading and payment-for-ecosystem-services programs while assisting countries in meeting greenhouse gas reduction targets established under international frameworks such as the Paris Agreement (FAO, 2021; IPCC, 2018). Consequently, land management strategies including conservation agriculture, agroforestry, afforestation, and improved soil management have been widely advocated as effective measures for increasing terrestrial carbon stocks and enhancing the resilience of agricultural systems to changing climatic conditions (Lal, 2018; FAO, 2021).

**Challenges**

Although carbon sequestration represents an important nature-based solution for reducing atmospheric greenhouse gas concentrations, its large-scale implementation is constrained by several scientific, technical, economic, and institutional limitations. A fundamental challenge is the finite capacity of soils and vegetation to retain carbon. Once these reservoirs approach carbon saturation, the rate of additional carbon storage declines substantially (Stewart et al., 2007). Furthermore, sequestered carbon is not permanently secured and may be lost through disturbances such as intensive





cultivation, deforestation, wildfires, soil erosion, prolonged drought, or changes in land use, resulting in the re-emission of stored carbon to the atmosphere (Lal, 2018).

Reliable quantification of soil organic carbon also remains a significant obstacle. Spatial heterogeneity in soil properties, inconsistencies associated with sampling procedures, and the financial burden of laboratory analyses and long-term monitoring complicate the measurement, reporting, and verification (MRV) of carbon stocks (Minasny et al., 2017). Beyond technical issues, widespread implementation is often hindered by socioeconomic constraints. Many carbon-enhancing management practices require substantial initial investment, specialized technical knowledge, and sustained management over extended periods. Limited financial incentives, insufficient awareness among farming communities, and uncertainties associated with carbon markets further reduce adoption rates (FAO, 2021). In addition, inconsistencies in carbon accounting methodologies and the lack of harmonized policy frameworks across regions restrict accurate valuation, verification, and commercialization of sequestration benefits.

### Way Forward

Expanding carbon sequestration at meaningful scales will require coordinated implementation of climate-smart land management strategies that promote long-term carbon storage while sustaining agricultural productivity. Practices such as conservation agriculture, agroforestry, biochar incorporation, and restoration of degraded ecosystems should be integrated within broader land management programs. Advances in remote sensing technologies, digital soil mapping, proximal sensing, and robust soil carbon monitoring systems can substantially improve the accuracy of carbon stock assessment and long-term verification. Simultaneously, strengthening carbon credit frameworks, developing standardized MRV protocols, investing in research

and innovation, and enhancing farmer capacity through extension services and financial incentives will be essential for accelerating adoption and ensuring durable environmental benefits.

### Conclusion

Carbon sequestration provides an effective pathway for simultaneously addressing climate change, improving soil quality, strengthening ecosystem resilience, and sustaining agricultural production. Enhancing carbon storage requires the integration of scientific advances, sustainable land management interventions, reliable monitoring systems, and supportive policy mechanisms. A coordinated approach involving researchers, policymakers, and land managers will improve the effectiveness of carbon sequestration initiatives, contribute to international climate commitments, and reinforce long-term environmental sustainability, agricultural resilience, and global food security.

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Hydroponics in Floriculture: Future of Flower Farming

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Introduction: A Blooming Revolution in Flower Farming

Floriculture, the cultivation of flowering and ornamental plants, has evolved from an ancient farming practice into a dynamic, high-growth global industry. From the simple joy of a gifted bouquet to the elaborate displays at weddings and state functions, flowers are a universal language of emotion and beauty. This deep-rooted cultural significance fuels a massive global floriculture industry, valued at over \$60 billion and projected to blossom to more than \$113 billion by 2032. Yet, the traditional soil-based farming methods that have long sustained this market are facing unprecedented pressure. This is due to a saturation effect, where further application of fertilizers only produces a marginal and diminishing return in productivity. Moreover, certain cultivable areas see poor soil fertility due to continuous cultivation which does not allow the soil to build-up its fertility over time due to growth of natural microbes. Limited arable land, increasing water scarcity, and the unpredictability of a changing climate pose significant threats to the future of flower cultivation (Thokchom et al.,2024).

In response to these challenges, a revolutionary technology is taking root, hydroponics. The word “HYDROPONIC” comes from a Greek word “hydro” means “water” and “ponos” means “labour”. The term is indicative of “waterwork”. Hydroponics is a technique of growing plants in nutrient solution apply all nutrient elements needed for optimum plant growth with or without the use of an inert medium such as gravel, vermiculite, rockwool, peat moss,

sawdust, coir dust, coconut fiber etc. to provide mechanical support.

Why Hydroponics Matters in Floriculture?

Flowers are delicate plants that require precise growing conditions. Hydroponics offer precise nutrient control, water efficiency, and faster plant growth, it promises year-round production of flawless, high-quality blooms using a fraction of the resources. They eliminate the need for soil, resulting in improved yields, reduced water use, and suitability for limited land areas. Hydroponics delivers nutrients through water, enabling fine-tuned monitoring, disease prevention, and reduced pesticide reliance.

From Babylon to Berkeley - The Roots of Hydroponics

Though the word "hydroponics" is a 20<sup>th</sup> century invention, soil-free cultivation dates back to ancient Babylon, Egypt, China, and India. The idea entered mainstream science in the 1920s and 1930s through William Frederick Gericke, a plant physiologist at UC Berkeley, who grew towering tomato vines using only mineral nutrient solutions and coined the term "hydroponics" in 1937.

Table:1. Traditional vs Hydroponics Floriculture: An Economic and Environmental Overview

| Metric      | Traditional Soil-Based Floriculture | Hydroponics Floriculture |
|-------------|-------------------------------------|--------------------------|
| Growth Rate | Baseline                            | 30-50%                   |



|                         |                                 |                                       |
|-------------------------|---------------------------------|---------------------------------------|
|                         |                                 | faster                                |
| Yield per Unit          | Baseline                        | 2-5 times higher                      |
| Water Usage             | Baseline                        | Up to 95% less                        |
| Land Requirement        | Requires arable land            | Can use 80% less land, no arable land |
| Pesticide/Herbicide Use | Common                          | Significantly reduced or eliminated   |
| Seasonality             | Dependent on climate and season | Year-round production                 |

### Hydroponic Systems for Commercial Floriculture

Hydroponic cultivation encompasses several distinct system designs; each tailored to particular crops and scales of production.

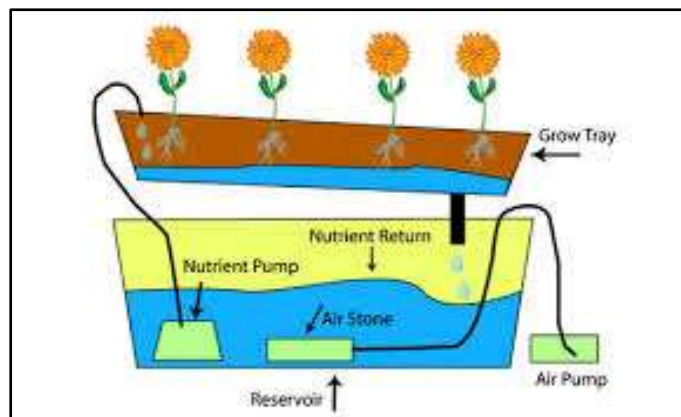
#### 1.Nutrient Film Technique (NFT)

In an NFT system, plants are placed in channels with their bare roots hanging into a shallow, continuously flowing stream or "film" of nutrient solution. This constant flow ensures roots receive ample nutrients and oxygen.

**Advantages:** Highly efficient in water and nutrient use; its modular design is well-suited for large-scale commercial operations.

**Disadvantages:** Vulnerable to power outages and pump failures, which can quickly lead to roots drying out.

**Best for Floriculture:** Smaller, fast-growing flowers with compact root systems, such as carnations, marigolds, and some herbs.



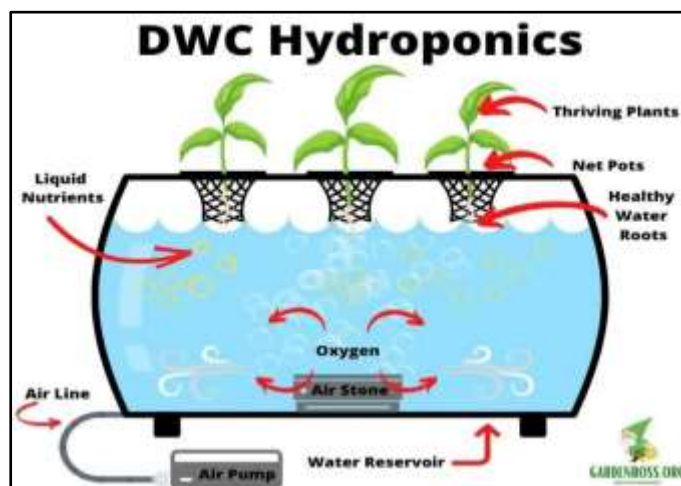
#### 2.Deep Water Culture (DWC)

DWC is one of the simplest active hydroponic systems. Plants are placed in net pots and suspended over a reservoir of highly oxygenated nutrient solution, with their roots submerged. An air pump and air stone are used to continuously aerate the water, preventing root rot.

**Advantages:** Simple and inexpensive to set up, making it popular with hobbyists and small-scale growers. Easy to monitor and adjust nutrient levels.

**Disadvantages:** Can be difficult to maintain a stable water temperature, and not ideal for very high-density plantings.

**Best for Floriculture:** Larger plants that require robust root support, such as roses, as well as bulb flowers like tulips and hyacinths, where the DWC method keeps the bulb itself out of the water.





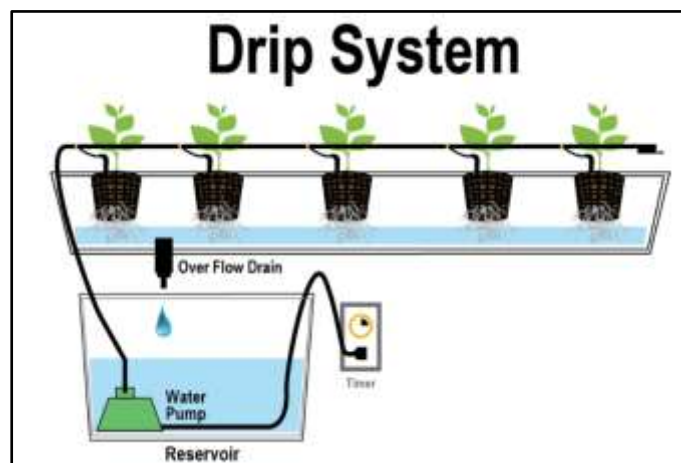
### 3.Ebb and Flow (Flood and Drain)

This system works by periodically flooding a grow tray containing plants in an inert medium (like perlite or clay pebbles) with nutrient solution from a reservoir. After a set time, the solution drains back into the reservoir.

**Disadvantages:** Relies on a timer and pump, making it susceptible to mechanical failure. The system must be well-designed to prevent root rot.

**Best for Floriculture:** Heavy-feeding flowers like dahlias that benefit from the excellent drainage and aeration provided by the substrate.

**Best for Floriculture:** A wide range of flowers, especially larger plants like lavender or those grown in individual containers.



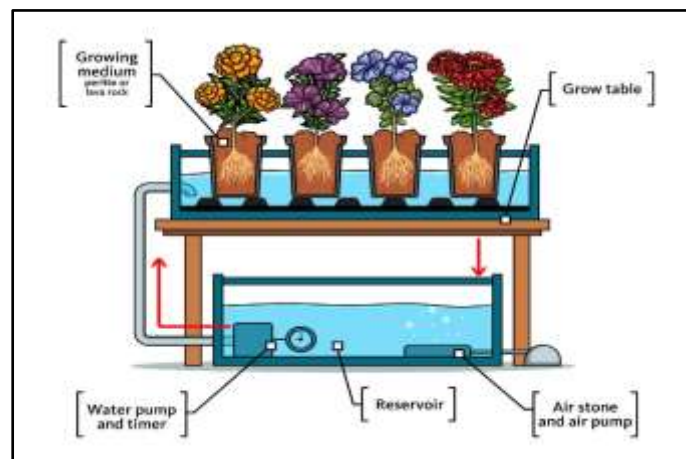
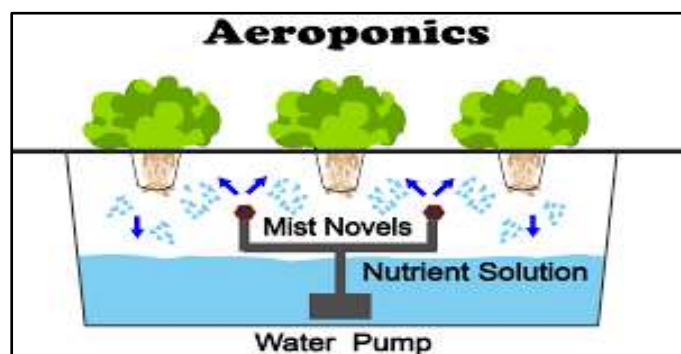
### 5.Aeroponics

It is considered as the most technologically advanced hydroponic method, aeroponics involves suspending plant roots in an enclosed, air-filled chamber and misting them with nutrient solution at regular intervals.

**Advantages:** Provides maximum oxygen exposure to the roots, often resulting in the fastest growth rates

**Disadvantages:** Highly dependent on electricity for pumps and short-cycle timers; any failure can be catastrophic to the plants. Requires a higher initial investment.

**Best for Floriculture:** High-value crops where rapid growth and yield are paramount. It has been successfully used for a variety of flowers.



### 4. Drip Systems

Among the most widely used commercial hydroponic methods, drip systems use a network of small tubes to drip a nutrient solution directly onto the base of each plant, which is typically grown in a substrate like coco coir or rockwool.

**Advantages:** Highly scalable and allows for precise control over the amount of solution each plant receives. Supports larger plants well.

**Disadvantages:** Drip emitters can clog, requiring regular maintenance. Non-recirculating versions can be less water-efficient.





### Advantages of Hydroponic Floriculture:

Hydroponic floriculture offers several clear benefits. By feeding roots a precisely balanced nutrient solution, plants are spared the energy of searching for nutrients, redirecting it into faster growth commonly reported as 40-50% quicker growth and 20-30% higher yields than soil-grown crops. This same nutrient control lets growers shape flower quality directly; in roses, it often produces more vibrant colour, stronger fragrance, and sturdier stems, boosting market value. Because hydroponics eliminates the need for arable land, cultivation becomes possible in deserts, rooftops, or warehouses, and vertical stacking lets growers match traditional yields on roughly a fifth of the land. Water efficiency is another major advantage: closed-loop systems can cut water use by 90-95% compared with soil farming, with some growers recycling up to 90% of irrigation water, a critical edge amid rising water scarcity. Finally, since indoor systems are shielded from weather and seasonal change, they deliver a steady, year-round supply of high-quality flowers, a reliability essential for commercial growers meeting constant market demand.

### Disadvantages of Hydroponics Floriculture:

Hydroponic floriculture also comes with notable challenges. It demands considerable technical skill to operate effectively, which can be a barrier for untrained growers (Sardare & Admane, 2013). Setting up the system requires heavy upfront investment in pumps, tanks, controls, and support infrastructure costs that can exclude growers with limited resources. Running pumps and lighting continuously also raises electricity costs, adding ongoing strain to profitability. Biological risk is another concern, as waterborne diseases can spread quickly, and system failure can trigger rapid, widespread plant loss. Finally, market perception remains a hurdle, as limited public familiarity with hydroponic produce can quietly dampen buyer

confidence, demand, and the prices growers can command (Pozníčková, 2019).

### The Economics of Elegance: Is Hydroponic Floriculture Profitable?

While the benefits are clear, the primary question for any commercial enterprise is profitability. Hydroponic farming does require a significant upfront investment in infrastructure, including greenhouses, pumps, lighting, and control systems (Sharma et al., 2018). Initial setup costs for a commercial hydroponic farm in India can range from ₹700 to ₹1,100 per square meter, depending on the level of automation and the specific system used (Barton Breeze, 2023).

### Future Research Directions and Innovations:

Hydroponic floriculture production is a rapidly evolving field, with new technologies and innovations constantly emerging to improve the efficiency, sustainability, and profitability of the systems.

1. **Vertical Farming:** Hydroponics serves as the backbone of vertical farming, allowing crops to be stacked in layers within warehouses, containers, or custom-built facilities. For flowers, this dramatically boosts yield per square foot, making large-scale production viable even in dense urban areas. It also shortens supply chains and lowers transport emissions, keeping fresher blooms reaching local markets year-round, independent of outdoor weather.
2. **Precision Agriculture:** Sensors, data analytics, and automation are helping optimize growth and resource use in hydroponic floriculture. Future research should focus on validating new sensors and algorithms, then integrating them smoothly into existing hydroponic management practices.
3. **Biotechnology and Genetic Engineering:** Biotechnology and genetic engineering hold



promise for making hydroponic flower production more efficient and sustainable. Yet these tools come with legitimate concerns i.e., ecological risks, possible health implications, and questions of public trust. Moving forward, research must address these concerns directly while working toward safer, more responsible ways to apply the technology.

4. **Renewable Energy and Sustainable Materials:** Renewable energy and eco-friendly materials are key to improving both the environmental and economic footprint of hydroponic floriculture. Solar, wind, and geothermal power can run lighting, heating, and cooling systems while cutting costs and emissions. This shift can also reduce waste and push the industry toward more recyclable and compostable materials.



### The Final Bloom: A Sustainable and Beautiful Future

The future of flower farming is here, and it is floating on water. Hydroponics is more than just a novel cultivation technique; it is a strategic response to the pressing agricultural challenges of the 21st century, paving the way toward a more sustainable, resilient, and profitable floriculture industry that can meet rising global demand without draining the planet's finite resources (Goddek, S. et al., 2019).

By conserving water, maximizing land use, and integrating advanced technology, hydroponic floriculture can produce flawless blooms year-round, anywhere. The upfront cost and energy demands are

real challenges, best met through renewable power, but the long-term benefits are clear; higher yields and control for farmers, superior and often local flowers for consumers, and a more sustainable path for the planet. The verdant revolution is in full swing, and in the flower farms of the future, there will be no soil, only the promise of a perfect, hydroponic bloom.

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# Hi-Tech Horticulture: A Catalyst for India's Economic Growth

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## Introduction

Horticulture occupies a central place in ensuring food and nutritional security, while also underpinning the economic wellbeing of everyone involved in the sector. Within this broader field, hi-tech horticulture stands out as a modern, capital-heavy, and environmentally conscious approach capable of lifting both output and profits for growers. As climate change reshapes farming conditions across India, adopting these advanced methods has shifted from being optional to essential if farmers hope to keep yields steady and incomes secure. The advantages of this approach extend well beyond growing fruits, vegetables, and flowers — they also touch conservation efforts, crop protection, and everything that happens after harvest, including adding value to raw produce. This piece looks at the different dimensions of advanced horticultural practice and considers where the field might head next.

At its core, hi-tech horticulture involves bringing sophisticated tools and methods into the production process to achieve better quality and stronger financial returns. This includes practices such as integrated pest and nutrient management, the use of hybrid and genetically modified planting stock, cultivation under protected structures, plastic-based farming techniques, micropropagation, drip and micro-irrigation systems, fertigation, hydroponic growing, precision agriculture, densely spaced planting, and mechanized operations, among other innovations. In broader terms, high-tech farming

describes any agricultural operation built around cutting-edge tools and techniques. Because it demands substantial investment — in specialized machinery, upkeep of assets, and training workers to handle new systems — it qualifies as a capital-intensive form of agriculture. For the most part, this style of farming is geared toward commercial operations that supply both domestic consumers and export markets. It leans on technological tools to raise productivity, deliver produce of consistently high quality (often with minimal reliance on chemical pesticides), and command better prices in the marketplace.

## Core Elements of Hi-Tech Horticulture

Hi-tech horticulture draws together a range of modern technologies spanning the entire horticultural value chain, from initial cultivation through to the final product reaching market. Its major components include:

### 1. Protected Cultivation

This practice involves raising horticultural crops within controlled settings such as greenhouses, polyhouses, net houses, and tunnel structures. Doing so shields plants from harsh weather, pest infestations, and disease, while also opening up the possibility of growing high-value crops — capsicum, tomato, strawberry, and gerbera among them — outside their usual growing season.



## 2. Micro-Irrigation and Fertigation

Drip and sprinkler-based irrigation systems channel water and nutrients straight to a plant's root zone, making both resources go further. Fertigation, which involves delivering fertilizers through the irrigation system itself, forms a central pillar of precision-based nutrient management.

## 3. Tissue Culture and Micropropagation

This technique supports the mass production of planting material that is both disease-free and genetically uniform. It has found widespread application across crops such as banana, potato, orchids, and various medicinal plant species.

## 4. Precision Horticulture

This approach draws on GPS technology, GIS mapping, sensor networks, drone imagery, and data analytics to track crop health, fine-tune input use, and push productivity higher. It makes it possible to intervene at very specific points within a field, ultimately boosting both yield and produce quality.

## 5. Integrated Pest and Disease Management (IPDM)

By combining biopesticides, pheromone traps, sticky traps, and decision-support tools for tracking pest activity, this strategy cuts down on chemical dependency while safeguarding the surrounding environment.

### Key Domains within Hi-Tech Horticulture

#### 1. Protected Cultivation

Greenhouses today are increasingly powered by solar panels and photovoltaic setups. Harnessing solar energy allows components like water pumps, UV filtration units, and lighting fixtures to run in a greener, more self-sufficient manner, often without needing constant manual oversight. A notable innovation in this space is the aquaponic solar greenhouse, which simultaneously produces crops,

fish, and clean energy under one system. Because of this combined output, the resulting food carries a remarkably small carbon footprint — in some cases, the system even functions as a net carbon sink rather than a source of emissions.

#### 2. Soil-less Farming

One striking example is the underground vertical hydroponic farm, which cuts water consumption by roughly 70 percent compared to conventional soil-based methods. This system relies on a closed-loop ebb-and-flow mechanism: nutrient-enriched water periodically floods the growing beds throughout the day before draining back into a storage reservoir, where it gets reused rather than discarded.

#### 3. Hydroponics

At its core, hydroponic cultivation aims to remove any obstacles that might otherwise stand between plant roots and the water, nutrients, and oxygen they need to thrive. Rather than growing in soil, plants are nourished through a solution of dissolved mineral fertilizers carried in water.

#### 4. Aeroponics

Aeroponic systems take this a step further by suspending plants in air or a fine mist, doing away with both soil and any solid growing medium entirely.

#### 5. Vertical Farming

Vertical farming stacks crop production in indoor environments where temperature, humidity, and nutrient levels are precisely regulated. This setup not only pushes yields higher but also reduces the broader environmental impact typically associated with traditional outdoor cultivation.

### Hi-Tech Horticulture in the Indian Context

Horticulture in India has evolved well beyond serving as a mere diversification strategy for farmers — it now stands as a cornerstone of both food and





nutritional security, alongside playing a vital role in safeguarding economic stability. States such as Maharashtra, Karnataka, Andhra Pradesh, and Kerala have seen tangible gains from embracing horticultural practices. With population numbers climbing steadily, pressure on natural resources has intensified, a problem made worse by global warming, changing climate patterns, increasingly fragmented landholdings, and rising expectations for premium-quality fresh produce.

Cryopreservation represents an area of considerable untapped promise for horticultural crops, yet it remains largely underutilized in practice. Work is currently underway to establish reliable cryopreservation methods for both pollen samples and explants derived from vegetative propagation across various horticultural species.

### Advanced Propagation Techniques

No horticultural enterprise can hope to succeed without consistent access to superior planting material. Micro-propagation has emerged as an effective means of multiplying plants quickly and in large numbers. This technique has already proven its worth with crops like banana (*Musa spp.*), bell pepper (*Capsicum annuum*), tomato (*Solanum lycopersicum*), chilli (*C. annuum*), and a range of ornamental species. Looking ahead, there remains considerable scope for expanding micropropagation efforts in India, particularly within the ornamental crop segment.

Plug-plant propagation offers its own set of advantages, producing seedlings that are healthy and free from viral infection. This approach also shortens the period before plants begin bearing fruit, promotes even growth across a crop, and simplifies the harvesting process. Meanwhile, grafting has established itself as an innovative hi-tech method applied to vegetable crops — most notably watermelon (*Citrullus lanatus*), capsicum, and brinjal. In fact, grafted vegetable seedlings are now

being cultivated at considerable scale in states like Chhattisgarh.

### Benefits of Adopting These Methods

- Yields can climb anywhere from five to eight times higher, translating into far greater output per unit of land
- Crop quality and growth consistency see marked improvement
- Critical inputs are used far more efficiently — water needs can drop by as much as half, fertilizer use by up to a quarter, with similar savings on pesticide application
- Farming becomes viable even in challenging terrain — including sloped land, saline soils, and areas prone to waterlogging
- Produce can be grown outside of its typical season
- Returns are no longer confined to a single harvest window but can be realized across the entire year
- Pressure on surrounding natural ecosystems is eased considerably
- Chemical runoff into rivers and groundwater supplies is significantly curtailed

### Future Prospects

Hi-tech horticulture holds real promise as a means of both doubling crop yields and helping achieve the broader goal of doubling farmers' income (DFI). For any hi-tech horticultural venture to succeed, it needs to capture live data from the field and relay it promptly to those making cultivation decisions, ensuring choices stay grounded in current, evidence-based insight rather than guesswork. A range of emerging technologies stand ready to support this shift — among them sensor networks, cloud-based computing platforms, augmented reality tools,





unmanned aerial vehicles, and control area networks (Ahrary and Ludena, 2015). When these tools are woven together with the practical, home-grown knowledge farmers already possess, the resulting synergy could carry hi-tech agriculture to entirely new levels of achievement.

### Conclusion

Hi-tech horticulture opens the door to cultivating a wide array of exotic plant varieties that might otherwise be difficult to grow. It also encourages farming under protected, controlled environments, which in turn helps planting material adapt and toughen against harsh or extreme weather conditions. Beyond this, the approach allows growers to supply produce during off-seasons and maintain a steady output across the entire calendar year. Given that so much of today's agricultural research is focused on building resilience against climate change, hi-tech horticulture emerges as a genuinely pioneering force in this pursuit. In the process, it has substantially strengthened the financial standing of farming communities.

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# Integrated Livestock Farming Systems: A Sustainable Approach for Enhanced Productivity and Resource Conservation

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## Introduction

Livestock play a vital role in global agriculture by providing milk, meat, eggs, fibre, manure, and draft power while contributing significantly to rural livelihoods. However, intensive livestock production often depends heavily on external inputs and may generate environmental challenges such as nutrient losses, greenhouse gas emissions, and waste accumulation. Integrated Livestock Farming offers a practical solution by linking livestock with other farm enterprises in a mutually beneficial system.

In an integrated farming system, the by-products of one enterprise become valuable inputs for another. Crop residues are utilized as animal feed, livestock manure is recycled as organic fertilizer or used for biogas production, and nutrient-rich slurry improves soil fertility. This circular approach enhances productivity while minimizing waste and environmental pollution. Consequently, Integrated livestock farming systems supports sustainable agriculture by improving farm profitability, conserving natural resources, and strengthening resilience against climate variability.

## Principles of Integrated Livestock Farming Systems

- Resource Recycling:** Crop residues are used as livestock feed, while animal manure is recycled as organic fertilizer or for biogas production.
- Enterprise Integration:** Different farm enterprises complement each other, increasing overall productivity and resource-use efficiency.
- Environmental Sustainability:** Recycling nutrients reduces waste, conserves natural resources, and minimizes environmental pollution.
- Economic Diversification:** Multiple enterprises generate diversified income, reducing financial risk and improving farm resilience.
- Efficient Resource Utilization:** Land, water, labour, and nutrients are used efficiently throughout the production cycle.

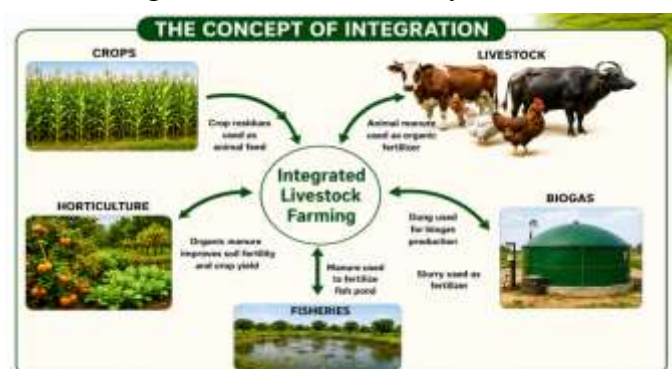
## Components of Integrated Livestock Farming Systems

### 1. Crop–Livestock System

Crop residues such as straw and stover are utilized as livestock feed, while animal manure is returned to fields to improve soil fertility and crop yield.

### 2. Livestock–Fish Farming

Animal manure is applied to fish ponds to stimulate the growth of natural fish food organisms, thereby improving fish production.



### 3. Livestock–Horticulture System

Farmyard manure and compost produced from livestock wastes enhance soil fertility and support the production of fruits and vegetables.

### 4. Livestock–Biogas System

Dung from cattle and buffalo is used to produce biogas for household energy. The digested slurry serves as an excellent organic fertilizer.

### 5. Agro forestry–Livestock System

Trees provide fodder, shade, fuelwood, and timber, while livestock contribute manure that improves soil fertility and supports tree growth.



#### Advantages

- Improves overall farm productivity and profitability.
- Generates multiple sources of income.
- Enhances soil fertility through nutrient recycling.
- Reduces dependence on chemical/ synthetic fertilizers.
- Minimizes environmental pollution.
- Strengthens food and nutritional security.
- Provides year-round employment opportunities.
- Increases resilience to climate change and market fluctuations.

#### Challenges

- Requires careful planning and efficient management.
- Higher initial investment in infrastructure.
- Need for technical knowledge and skilled labour.
- Greater complexity in disease prevention and biosecurity.
- Limited access to quality inputs, credit, and extension services in some regions.

#### Future Prospects

Integrated Livestock Farming System is increasingly recognized as a key strategy for sustainable agriculture. The adoption of technologies such as precision livestock farming, artificial intelligence, IoT-based monitoring, renewable energy systems, and climate-smart practices can further improve productivity, resource-use efficiency, and environmental sustainability. Supportive government policies, farmer training, and improved market access will accelerate its adoption.

#### Conclusion

Integrated Livestock Farming is an economically viable and environmentally sustainable farming system that promotes efficient resource recycling, diversified income, and improved farm resilience. By integrating livestock with complementary agricultural enterprises, it enhances productivity while conserving natural resources. As global demand for sustainable food production continues to grow, Integrated Livestock Farming will play an increasingly important role in ensuring food security, environmental conservation, and long-term agricultural sustainability.

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# VIROSIS: A Silent Threat to Tropical Tasar Silkworms

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## Introduction

Tropical tasar sericulture is an important forest-based enterprise that provides sustainable livelihoods to thousands of tribal and rural families across India. Besides generating employment and income, it contributes to biodiversity conservation, sustainable utilization of forest resources, and the production of premium quality wild silk. The success of tasar sericulture, however, largely depends on maintaining healthy silkworms throughout the rearing season. Healthy silkworms are the foundation of superior cocoon production and high-quality silk. Any factor that affects larval health directly influences cocoon yield, shell ratio, and the quality of the silk filament. Among the various biotic constraints, diseases remain one of the major causes of economic losses in tropical tasar sericulture, with viral diseases (virosis) being particularly destructive.

Virosis is estimated to account for **25 - 30% of seasonal crop losses**, causing severe larval mortality and substantial deterioration in both cocoon yield and silk quality. Since tropical tasar silkworms (*Antheraea mylitta* Drury) are reared under natural outdoor conditions on their primary host plants, **Arjun (*Terminalia arjuna*)** and **Asan (*Terminalia tomentosa*)**, they are continuously exposed to fluctuating weather conditions, insect vectors, and environmental contaminants that favour the spread of viral pathogens. High humidity, elevated temperatures, prolonged rainfall, and poor field sanitation further increase the risk of disease outbreaks. Unlike many other production constraints,

viral diseases have **no curative treatment once infection is established**. A sound understanding of virosis and its management enables farmers to safeguard their crops, improve cocoon productivity, produce better-quality silk, and enhance the profitability and sustainability of tropical tasar sericulture.

## What Causes Virosis?

Virosis in tropical tasar silkworms is primarily caused by the *Antheraea mylitta* Cytoplasmic Polyhedrosis Virus (AmCPV), a double-stranded RNA virus belonging to the family Reoviridae. The virus mainly attacks the midgut of the silkworm larvae, disrupting digestion and nutrient absorption. The disease is commonly known as tasar grasserie and spreads rapidly under high humidity, elevated temperatures, poor sanitation, and contaminated host plant leaves.

## Symptoms of Virosis

Early identification of infected larvae is essential to reduce disease spread. Regularly monitor their silkworms for the following signs:

- Loss of appetite and reduced feeding activity
- Sluggish movement and weak gripping ability on host plant branches
- Soft, flaccid body with altered shape
- Enlarged head or unusually long body bristles





- Larvae become elongated and develop a characteristic brownish discoloration
- Advanced infections eventually result in larval death, reducing the number of marketable cocoons



*AmCPV* affected worms

### Impact of Virosis on Cocoon production

The impact of viral infections extends beyond larval mortality; surviving larvae frequently produce inferior-quality cocoons. Consequently, infected crops typically exhibit:

- Decreased cocoon weight
- Lower shell weight
- Shorter continuous silk filaments
- Reduced non-breakable filament length
- Diminished raw silk quality and reelability

These qualitative losses ultimately depress farmers' income and undermine the overall profitability of tropical tasar sericulture.

### Management Practices

#### Prevention Is the Best Cure

There is no effective chemical treatment once a viral infection becomes established in the rearing field.

Therefore, disease prevention through scientific management is the most reliable strategy.

#### Maintain strict sanitation.

Clean rearing fields, remove diseased larvae immediately, and disinfect rearing equipment and surroundings using recommended disinfectants to destroy viral particles.

#### Use healthy seed

Always procure Disease-Free Layings (DFLs) from certified grainages to minimize the risk of introducing infection at the beginning of the crop.

#### Protect silkworms from adverse weather

High humidity and prolonged rainfall favor viral outbreaks. Where feasible, use protective nylon nets or other recommended rearing practices to minimize weather-related stress.

#### Ensure healthy host plants

Feed larvae only with fresh, healthy leaves from well-managed Arjun (*Terminalia arjuna*) and Asan (*Terminalia tomentosa*) plantations. Avoid feeding leaves contaminated with dust, disease, or excessive moisture.

#### Adopt eco-friendly interventions

Application of recommended botanical and biological formulations of Jeevan Sudha

**Jeevan Sudha** is a botanical prophylactic formulation developed by the Central Tasar Research & Training Institute (CTR&TI), Central Silk Board, for the management of virosis in tropical tasar silkworms. The required quantity of powder is soaked in water for 8–10 hours, filtered, and the 1% aqueous extract is sprayed on host plant foliage and larvae 24 hours after moulting during the 2nd, 3rd, and 4th instars. For 200 DFLs, use 50 g in 5 L water (1st instar), 100 g in 10 L (2nd instar), and 150 g in 15 L (3rd instar). Regular application helps





reduce viral infection, improves larval survival, and enhances cocoon productivity.



### Conclusion

Virosis remains one of the biggest challenges in tropical tasar sericulture, but its impact can be greatly reduced through timely monitoring, clean rearing

practices, healthy seed, proper host plant management, and scientific disease prevention measures. By adopting these simple yet effective practices, tasar farmers can improve larval survival, produce better-quality cocoons, and enhance their income while ensuring the longterm sustainability of tropical tasar silk production.

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# Farm-Grown Timber Trees - The Hidden Carbon Reservoirs of Agroforestry Landscapes

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Agricultural landscapes are generally viewed as areas of food production, while forests are recognised as major reservoirs of carbon. However, this distinction overlooks the large number of timber trees growing on farms, field boundaries, homesteads and other non-forest lands. These trees continuously absorb atmospheric carbon dioxide through photosynthesis and store it in their stems, branches, leaves and roots. They also transfer carbon to the soil through litterfall, root turnover and decomposition. Farm-grown timber trees therefore function as hidden carbon reservoirs within productive landscapes. When carefully integrated with crops, they can improve resource-use efficiency, protect soil, regulate microclimate, support biodiversity and provide farmers with timber and long-term income. Agroforestry offers a practical approach for combining agricultural production with environmental conservation and climate resilience (Maitra *et al.*, 2024). Nevertheless, the carbon contribution of scattered farm trees is often underestimated because they are not always included adequately in conventional forest inventories. This article explains the concept and process of carbon sequestration in farm-grown timber trees, identifies the major carbon pools in agroforestry systems and discusses their environmental, economic and social importance. It also highlights suitable management practices, existing challenges and future opportunities for recognising farm trees as an integral component of climate-smart and sustainable agricultural development.

## 1. Introduction

Climate change has become one of the most significant environmental challenges confronting agriculture and rural livelihoods. Increasing temperatures, irregular rainfall, prolonged droughts, intense storms and soil degradation are placing additional pressure on farming systems. At the same time, agriculture must continue producing food, fodder, fibre, fuel and raw materials for a growing population. Meeting these demands requires land-management systems that support production without further weakening the natural-resource base. Trees can make an important contribution to this transformation. Although discussions of tree-based carbon storage commonly focus on natural forests and large plantations, millions of trees also grow outside officially classified forests. They are found within agricultural fields, along farm boundaries,

around water bodies, near houses and roads and in mixed crop–tree systems. Individually, these trees may appear scattered and insignificant; collectively, however, they form a substantial biological resource across rural landscapes. Farm-grown timber trees are generally established or retained to produce wood, poles, fuel, shade, shelter or future income. They may be planted in compact blocks, rows, shelterbelts or boundary strips, or dispersed among agricultural crops. This integration of trees with crops and sometimes livestock forms the basis of agroforestry. Agroforestry is not simply the presence of trees on agricultural land; it is the deliberate management of different biological components so that they interact productively and sustainably. Maitra *et al.*, (2024) describe agroforestry as a resource-conserving technology capable of improving the use of agricultural inputs while contributing to food and



environmental security. Trees can capture resources from different levels of the soil and atmosphere, recycle nutrients, reduce erosion and produce valuable biomass. Consequently, farm-grown timber trees should be recognised not only as commercial assets but also as living components of the terrestrial carbon cycle.

## 2. The Concept of Farm-Grown Timber Trees

Farm-grown timber trees are woody perennial species cultivated on privately managed agricultural or associated lands mainly for timber and other useful products. Unlike trees in natural forests, they are maintained as part of a working agricultural landscape and are influenced directly by farmers' choices regarding species, spacing, pruning, protection, rotation and harvesting. Farm forestry may take several forms. Trees can be established around the outer boundary of a field, planted in rows between crops, cultivated as small woodlots or incorporated into multistoreyed home gardens. Some farmers maintain naturally regenerated trees, while others plant commercially preferred timber species. In each case, the trees share the landscape with agricultural activities and contribute to both production and ecological functioning. Agroforestry is based on the principle that trees, crops and livestock can use resources differently across space and time. Annual crops mainly occupy the upper soil layers and complete their life cycle within a season, whereas trees remain for several years and develop deeper, more extensive root systems. This structural difference can allow a well-designed system to capture sunlight, water and nutrients more efficiently than a simplified production system (Maitra *et al.*, 2024).

The concept is therefore broader than tree planting. It involves selecting suitable species, designing compatible arrangements and managing interactions so that trees complement rather than severely compete with agricultural crops.

## 3. Why Are They Called Hidden Carbon Reservoirs?

Farm-grown timber trees may be described as hidden carbon reservoirs for three main reasons. First, they are widely distributed across small and fragmented holdings rather than concentrated within a continuous forest. Their scattered distribution makes them difficult to map and monitor through conventional land-use classifications. Second, agricultural land is commonly identified according to its principal crop. A field containing boundary trees, scattered timber trees or small woody patches may still be recorded simply as cropland. As a result, part of its tree biomass can remain poorly represented in regional carbon assessments. Third, much of the carbon stored by trees is not immediately visible. The trunk is the most prominent component, but carbon is also present in branches, bark, foliage and roots. Additional carbon occurs in fallen litter, dead roots, soil organic matter and harvested timber products. A single farm tree may hold only a small proportion of landscape-level carbon, but the combined contribution of numerous trees across thousands of farms can be considerable. Their importance becomes especially clear when carbon storage is considered together with soil protection, farm income, biodiversity and climate resilience.

## 4. The Process of Carbon Sequestration

Carbon sequestration is the process through which carbon dioxide is removed from the atmosphere and stored in another reservoir. In an agroforestry system, this process involves several connected stages.

### 4.1. Capture through photosynthesis

The process begins in the leaves. Trees absorb atmospheric carbon dioxide through microscopic openings called stomata. Using sunlight, water and chlorophyll, they convert carbon dioxide into carbohydrates through photosynthesis. Some of these carbohydrates provide energy for maintenance and respiration. The remainder supplies the raw material



needed to form new leaves, branches, wood and roots. The continuous growth of a tree therefore represents the gradual conversion of atmospheric carbon into plant biomass.

#### 4.2 Storage in above-ground biomass

As a timber tree grows taller and wider, carbon accumulates in its stem, branches, bark and crown. The stem generally represents the largest commercial component and often forms a major share of above-ground biomass. Diameter growth is particularly important because a small increase in stem thickness can represent a substantial addition of woody biomass. However, carbon accumulation depends on species, age, wood characteristics, climate, soil fertility, moisture, competition and management. Trees do not accumulate carbon at an identical rate throughout their lives. Young trees invest heavily in establishment and height development. During intermediate stages, favourable conditions may support rapid crown and stem growth. Mature trees normally contain a greater standing carbon stock because biomass has accumulated over a longer period, although their annual growth rate may differ from that of younger trees.

#### 4.3 Movement of carbon below ground

Carbon storage does not stop at the soil surface. Part of the carbohydrates produced in the leaves is transported downward to support the root system. Large structural roots store carbon and anchor the tree, while fine roots absorb water and nutrients. Fine roots have shorter life cycles and are continuously produced, shed and replaced. Their death introduces organic matter directly into the soil. Living roots also release carbon-rich compounds known as root exudates. These compounds provide energy to soil microorganisms and influence nutrient availability, soil aggregation and biological activity. Below-ground biomass is difficult to observe and measure, but it represents an essential part of the tree's carbon contribution.

#### 4.4 Litterfall and organic inputs

Leaves, flowers, fruits, bark and small branches eventually fall onto the soil surface. This material is collectively known as litter. Litterfall is the principal pathway through which carbon and nutrients move from the tree canopy to the soil surface. The quantity and quality of litter vary among tree species, seasons and growth stages. Leaves rich in easily decomposable compounds may break down quickly, while lignin-rich woody materials generally persist longer. Rainfall, temperature, soil moisture and decomposer organisms also affect the rate of decomposition.

#### 4.5 Decomposition and soil-carbon formation

Bacteria, fungi, termites, earthworms and other soil organisms break litter and dead roots into progressively smaller components. During this process, part of the carbon is released back into the atmosphere through microbial respiration. Another portion is incorporated into microbial biomass or transformed into soil organic matter. Some organic carbon may become protected within soil aggregates or attached to clay and mineral particles. This stabilised carbon can remain in the soil for longer periods than rapidly decomposing surface residues. Tree roots and litter can therefore contribute to the formation and maintenance of soil organic carbon. Agroforestry may improve soil conditions through continued organic inputs, better surface protection and nutrient cycling. Its success nevertheless depends on the compatibility of trees with crops and the quality of management adopted (Maitra *et al.*, 2024; Kandileri *et al.*, 2024).

#### 4.6 Storage in harvested wood products

Harvesting a tree does not necessarily result in the immediate release of all its stored carbon. Timber used in buildings, furniture, doors and other durable products may retain carbon for many years. By contrast, wood used as fuel or converted into short-lived products returns carbon to the atmosphere



relatively quickly. The final climate benefit of farm forestry therefore depends partly on what happens after harvesting. Efficient conversion, minimum processing waste and the use of timber in durable products can extend carbon storage beyond the tree's standing life.

## 5. The Major Carbon Pools

The carbon contained in an agroforestry landscape is distributed among several connected pools.

### Above-ground biomass

This pool includes the stem, branches, bark and leaves of living trees. It is the most visible carbon pool and the easiest to assess through tree measurements. Its size is influenced by tree dimensions, crown development, wood density and management history.

### Below-ground biomass

This pool consists of coarse and fine roots. Coarse roots can hold carbon for long periods, while fine-root turnover contributes continuously to soil organic matter. Ignoring roots can lead to an incomplete understanding of tree-based carbon storage.

### Litter and dead organic matter

Fallen leaves, twigs, bark, dead roots and woody debris form an intermediate pool between living vegetation and soil. Although much of this material eventually decomposes, it protects the soil surface, supports nutrient cycling and provides energy for decomposer organisms.

### Soil organic carbon

Soil organic carbon develops from decomposed plant residues, root inputs, microorganisms and other organic materials. It is an important but highly variable pool. Soil texture, moisture, temperature, vegetation history, erosion and cultivation practices influence its formation and stability.

## Harvested wood products

Timber converted into durable products continues functioning as a carbon reservoir outside the farm. Its storage period depends on the lifetime of the product, reuse, recycling and final disposal. These pools should not be considered independently. Carbon moves continuously among the atmosphere, vegetation, litter, soil and wood products. A complete assessment must recognise the entire system.

## 6. Livelihood Security and the Idea of Biohappiness

Farm-grown timber trees are long-term biological assets. Farmers may harvest them to meet major household needs such as education, healthcare, housing or reinvestment in agriculture. Trees can also produce fuelwood, poles, fodder, fruits, shade and other useful products before the final timber harvest. This combination of environmental protection and livelihood improvement reflects the broader concept of "biohappiness." Swaminathan (2015) emphasises that biodiversity conservation should be linked with sustainable and equitable use so that biological resources generate food, employment, income and security. Within this perspective, the success of farm forestry should not be judged only by tonnes of biomass or carbon. It should also be evaluated by whether farmers receive meaningful benefits, whether biodiversity is protected and whether land remains productive for future generations. Farm forestry can diversify income and reduce dependence on a single seasonal crop. Nevertheless, farmers face challenges such as long rotation periods, uncertain timber prices, poor-quality seedlings, limited technical guidance and complicated harvesting or transport procedures. Effective extension services and transparent markets are therefore as important as the biological potential of the trees.





## 7. Managing Agroforestry for Greater Carbon Benefits

A carbon-friendly agroforestry system begins with appropriate species selection. Trees should be suited to local soil, rainfall, temperature and water availability. They must also match the farmer's objectives and the ecological requirements of associated crops. Spacing should provide sufficient room for tree development without creating severe competition. Boundary planting may be appropriate where farmers wish to retain most of the field for annual crops, while block planting may be more suitable where timber is the principal objective. The soil carbon pool should be protected by minimising unnecessary burning, excessive soil disturbance and complete removal of organic residues. Suitable amounts of litter can be retained to protect the surface and support biological activity. Harvesting should be accompanied by regeneration or replanting. If all trees are removed and not replaced, the landscape loses both its standing carbon and its capacity for future sequestration. Staggered harvesting can provide income while maintaining continuous tree cover. Healthy growth requires regular monitoring, protection from grazing and fire and timely management of pests and diseases. Timber should, wherever practical, be directed towards durable uses that extend the period of carbon storage. These practices support the broader goal of achieving production efficiency alongside food and environmental security, as emphasised by Maitra *et al.*, (2024).

## 8. Challenges and Important Cautions

Tree planting is valuable, but it should not be presented as a simple or universal solution to climate change. Carbon accumulation differs among species, sites and management systems. Estimates developed for one region cannot automatically be applied to another. Carbon permanence is another concern. Fire, drought, storms, pests, disease, land conversion and premature harvesting can reduce or reverse stored

carbon. Long-term monitoring and risk management are therefore necessary. Poorly planned tree planting can also create undesirable outcomes. Unsuitable species may compete strongly for water, reduce crop yields or threaten local biodiversity. Large monocultures may be vulnerable to pests and market fluctuations. Carbon-focused interventions must not undermine food production, farmers' rights or access to land. Participation in formal carbon markets presents additional difficulties. Measurement, reporting and independent verification can be costly for individual smallholders. Farmer groups, cooperatives and landscape-level programmes may be better positioned to share these costs. Clear rules are also needed regarding ownership of carbon benefits, payment distribution and responsibility when trees are lost. The environmental benefits documented for short-rotation forestry illustrate why farm-tree systems should be assessed through multiple outcomes rather than carbon alone (Updegraff, 2002).

## 9. Future Prospects

The future of sustainable agriculture lies in multifunctional landscapes that produce food and raw materials while conserving soil, supporting biodiversity and responding to climate change. Farm-grown timber trees can contribute strongly to this transition. Improved remote sensing, mobile inventories, geographic information systems and simpler field protocols can make scattered farm trees easier to document. Long-term studies can strengthen understanding of tree-crop interactions, root dynamics, litter decomposition, soil-carbon stability and the effects of harvesting. Policy support should include quality planting materials, site-specific technical guidance, farmer-friendly harvesting regulations, transparent timber markets and practical methods for carbon monitoring. Most importantly, farmers must remain central to planning and benefit sharing. As Swaminathan (2015) argues through the concept of biohappiness, biological resources should be conserved and used in ways that generate



ecological, economic and social well-being. Farm forestry can serve this purpose when carbon storage, food security and livelihood improvement are pursued together.

## 10. Conclusion

Farm-grown timber trees are more than sources of wood. They are living carbon reservoirs distributed throughout agricultural landscapes. Through photosynthesis, they remove carbon dioxide from the atmosphere and store carbon in stems, branches, leaves and roots. Litterfall, root turnover and decomposition transfer part of this carbon into the soil, while durable timber products may retain carbon after harvesting. Their importance extends well beyond climate mitigation. Properly managed farm trees can protect soil, recycle nutrients, regulate microclimate, support biodiversity and provide farmers with long-term economic security. Agroforestry therefore offers a practical means of linking agricultural production with resource conservation and environmental security (Maitra *et al.*, 2024). However, successful farm forestry requires more than planting large numbers of trees. Species must be suited to the site, tree–crop competition must be managed, soil organic matter must be protected and harvested trees must be replaced. Carbon benefits should be evaluated alongside food production, biodiversity and farmer welfare. Recognising these hidden reservoirs can change the way agricultural landscapes are understood. A farm is not necessarily a treeless production unit; it can be a dynamic mosaic in which crops, trees, soil and people contribute collectively to

climate resilience. Supporting farm-grown timber trees can therefore strengthen both terrestrial carbon management and the long-term sustainability of rural livelihoods.

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## Rinderpest (Cattle Plague)

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Rinderpest is an acute, highly contagious disease of cattle caused by a morbillivirus. The disease has been the foremost cause of death in cattle in most African and Asian countries, including India. In fact, the need to fight the disease was instrumental in the establishment of the first veterinary college in 1762 in Lyon, France. Mortality varies from 25%-90%, depending on the strains of virus and the resistance of the animals. Clinically, the disease is characterized by high fever, necrotic stomatitis, diarrhoea, and high mortality. Buffaloes, sheep, pigs, goats, and camels are also susceptible. In wildlife, rinderpest has been reported in deer, antelope, wild buffaloes, wild boars, bushbuck, warthogs and giraffe. The rinderpest virus is anti-genetically closely related to the viruses of canine distemper, peste-des-petits-ruminants (PPR) of sheep and goats, and measles of humans. Many strains of rinderpest virus occur, but all are immunologically identical. Therefore, the immunity which develops after infection, or vaccination with one strain, protects against all other strains. Rinderpest has not been reported since June 1995 in our country.

**Synonyms-** Cattle Plague, Bovine typhus, Bulkhandi.

**Etiology-** it is caused by Paramyxovirus.

### Spread

Rinderpest virus is quite fragile. Therefore, close contact between infected and non-infected animals is necessary for spread of the disease, because the virus does not survive for long outside the host. The virus is excreted by infected animals in urine, faeces, nasal discharges, and sweat. Transmission occurs through contaminated feed, or by inhalation of aerosol (infected droplets). Ingestion of food contaminated by the discharges of clinical cases, or animals in the incubation stage, may also be important modes of infection, especially in pigs.

### Pathogenesis

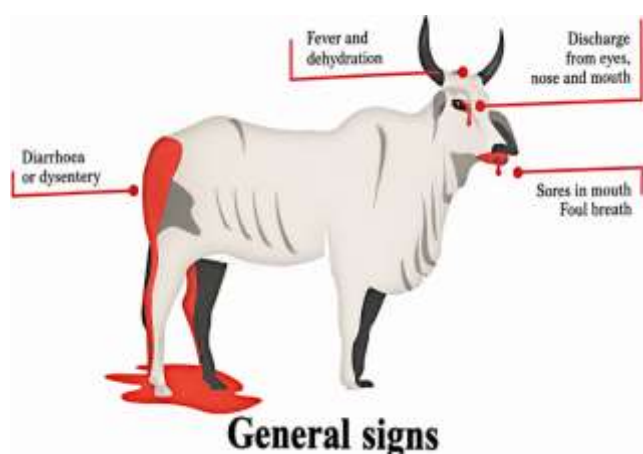
The virus is inhaled in infected droplets. It penetrates through the epithelium of the upper respiratory tract and multiplies in the tonsils and regional lymph nodes. From here it enters the blood in mononuclear

cells, which disseminate the virus to other lymphoid organs, the lungs, and epithelial cells of mucous membranes. The virus has a high degree of affinity for lymphoid tissue and alimentary mucosa. There is a pronounced destruction of lymphocytes in tissues. This is the cause of marked leukopenia. The virus is intimately associated with leukocytes, only a small proportion being free in plasma. The focal, necrotic stomatitis and enteritis are the direct result of the viral infection and replication in the epithelial cells in the alimentary tract. However, since the virus induces a strong antibody response shortly after infection, there is a rapid decrease and elimination of virus from the body as the clinical signs and lesions become visible. Death is usually from severe dehydration, but in less acute cases, death may be from activated latent parasitic or bacterial infections. These aggravate because the animal is immunosuppressed as a result of the destruction of lymphoid organs by the virus.



## Signs

The onset of illness is indicated by a sharp rise in body temperature (104 – 105°F), accompanied by restlessness, dryness of the muzzle, and constipation. Other signs include photophobia (intolerance to light), excessive thirst, starry (shining) coat, retarded rumination, anorexia, and excessive salivation. A maculo-papular rash may develop on parts of the body, where hairs are fine. The fever usually reaches its peak on the 3<sup>rd</sup> or 5<sup>th</sup> day, but drops abruptly with the onset of diarrhoea, even though other symptoms get intensified. Lesions in the oral mucosa may appear by the 2<sup>nd</sup> or 3<sup>rd</sup> day of fever, but become clearly visible only after the onset of diarrhoea. As the diarrhoea increases in intensity, it is accompanied by abdominal pain, increased respiration, severe dehydration, and emaciation. This is followed by prostration, subnormal temperature, and death, usually after a course of 6-12 days. A marked leukopenia occurs at the height of infection. The total count usually falls to below 4000/~1, and is due to an abrupt drop in lymphocytes. Immunity after a natural infection is long and persists for life. The protection is associated with the induction of humoral antibodies, first IgM, and later IgG and IgA.



## Lesions

As already mentioned, the rinderpest virus has a particular affinity for epithelial tissues of the gastrointestinal tract, where it produces severe characteristic changes. In lymphoid tissue, the virus

causes necrosis of lymphocytes. This is striking in microscopic sections of lymph nodes, spleen, and Peyer's patches. The destruction of Lymphocytes is first seen as a fragmentation of nuclei in the germinal centres, and in a short time, most of the mature lymphocytes disappear. Multinucleated giant cells containing eosinophilic cytoplasmic inclusion bodies are often present. Rarely, intranuclear inclusions are also seen. Oedema and congestion of capillaries are seen microscopically. The destruction of lymphoid cells leaves a fibrillar, eosinophilic, acellular matrix at sites of the Lymphoid follicles. Grossly, changes are most marked in the Peyer's patches, which may be darkened with haemorrhages and slough out, leaving deep craters (ulcers) in the intestinal wall. In the digestive system of cattle, rinderpest virus produces typical lesions. The virus is carried to the oral mucosa by the bloodstream. In the squamous epithelium of the oral cavity, the first change is necrosis of a few epithelial cells in deep layers of the stratum Malpighi. These cells have pyknotic and fragmented nuclei and eosinophilic cytoplasm. They are shrunken and separated from the adjoining space by a clear space. As these necrotic areas increase in size and extend towards the surface, the cornified layer above them becomes elevated. This causes them to appear grossly as tiny, greyish white, slightly raised puncta (points). Multinucleated giant cells form in the stratum spinosum. Eosinophilic cytoplasmic inclusion bodies form in the mucosal epithelial cells and giant cells. Intranuclear inclusion bodies are rare. Vesicles are not formed in this disease. With time, the foci of necrosis coalesce to form large areas of erosions. Since the basal layer of the squamous epithelium is rarely penetrated, ulcers seldom form. The erosions are shallow, with a red raw floor, and a sharply demarcated margin. The lesions in the oral mucosa have a selective distribution: inside the lower lip, the adjacent gum, the cheeks near commissures, and the ventral surface of the free portion of the tongue. In severe cases, lesions extend to the hard palate and pharynx, and in fulminant cases, to all the mucous surfaces of the





tongue. The oesophageal lesions are similar to those in the mouth, but are less severe. The rumen, reticulum, and omasum rarely exhibit any lesions. The abomasum is one of the most common sites of the lesions of rinderpest. They are most severe in the pyloric region, where necrotic foci of microscopic size in the epithelium are accompanied by congestion and haemorrhage in the underlying lamina propria. Grossly, this results in irregular superficial bright red to dark brown streaks. These streaks follow the edges of the broad plicae and extend into the fundus, but become more numerous and diffuse in the pylorus. Oedema may be extensive in the submucosa of plicae, making it to appear thickened. As necrosis of the epithelium progresses, the epithelium sloughs away, leaving sharply outlined irregular erosions with a red raw floor oozing blood. In the small intestine, severe lesions are less common than in the mouth, abomasum, or large intestine. However, Peyer's patches are exceptionally vulnerable. The lymphoid tissue may become so necrotic that patches slough out, leaving deep raw craters in the intestinal wall.

The large intestine, as a rule, is more seriously damaged than the small intestine, with prominent lesions in the ileo-caecal valve, caeco-colic junction, and the rectum. The crest of the folds of mucous membrane throughout the caecum is bright red because of numerous petechiae, which appear more like diffuse haemorrhages. Microscopically, the petechiae (haemorrhages) are markedly distended capillaries, packed with erythrocytes, in the lamina propria. Streaks of congestion along the folds of mucosa produce a characteristic **"Zebra-striped" (Zebra markings)**, or **"barred" appearance**. As the disease progresses and the mucosa becomes eroded, diffuse congestion and bleeding from the raw surfaces may occur over large areas. When opened, the mucosa is diffusely red, and the lumen contains partially clotted blood. Lesions at the caeco-colic junction include congestion, erosion, and increased thickness of the wall, partly the result of oedema in

the submucosa and muscularis. The changes in the colon and rectum vary from a few longitudinal streaks of congestion along the crest of the folds of the mucosa to erosions of the mucosal epithelium. The characteristic streaks of congestion and haemorrhage are more common and striking in the rectum than in the colon. The liver is affected only secondarily in rinderpest, with chronic passive congestion resulting from cardiac and pulmonary complications. Lesions in the gallbladder vary from scattered petechiae to diffuse blotches of haemorrhage. In the respiratory system, the epithelium is susceptible to the virus. Petechiae occur on the turbinates and larynx. In the trachea, streaks of haemorrhages in the mucosa are almost always found. Most common are longitudinal streaks of rusty haemorrhage in the anterior third of the trachea. The lungs appear to be involved only secondarily. In acute cases, lungs usually appear grossly normal. In long-standing cases, lesions include both interlobular and alveolar emphysema and small areas of consolidation. The lesions of the heart also appear to be secondary and include subendocardial haemorrhages over the papillary muscles of the left ventricle. The right ventricle is seldom involved. In the urinary system, lesions comprise oedema around the renal pelvis and desquamation of pelvic epithelium. In the urinary bladder, the epithelium may be desquamated and the underlying stroma infiltrated with erythrocytes. The infiltrates are grossly seen as thin red blotches. Lesions in the skin, though not common, may be seen as a maculopapular rash over thinly haired portions of the body, the vulva, and prepuce. Microscopically, they resemble those of the oral mucosa. A virus very closely related to rinderpest, and causing an acute, highly fatal disease of sheep and goats is called "peste-des-petits-ruminants (PPR)". It does not naturally affect cattle, nor does experimental infection lead to disease in cattle. It does, however, confer immunity to rinderpest virus.





## Diagnosis

The clinical, gross, and microscopic features of the disease are adequate for a presumptive diagnosis. This should, however, be confirmed by immunological methods which include a gar gel immunodiffusion (AGID), complement fixation, counter-immunoelectrophoresis (CIEP), immunofluorescence, and immuno-peroxidase tests, an ELISA which is accurate and easy to perform, and a rapid dot-enzyme immunoassay test suitable for field use. Using specific cDNA probes, isolates of rinderpest and PPR viruses can now be differentiated. A test employing the polymerase chain reaction (PCR) has been developed that can detect viral RNA in tissues otherwise unsuitable for standard techniques. Isolation of the virus and its identification are now possible in tissue culture to confirm the diagnosis.

## Treatment:-

- No effective treatment and treatment very little help in rinderpest.
- Rinderpest Antiserum 1m/kg bd wt. I/V route.
- Antibiotics like Penicillin, Streptomycin, Oxytetracycline should be used to control Secondary bacterial and protozoal infections.
- Astringents or antidiarrheal drugs.
- Large doses of fluid and electrolytes beneficial to counter excessive dehydration like Dextrose Saline IV.

## Control and Prevention:-

- Complete prohibition of imports of domestic ruminants, pigs and animal products from enzootic areas.
- If disease breaks out, controlled by slaughter of infected, restrictions of stock movement.

- Quarantine and check posts opened to prevent entry of infected cattle.

## Vaccination

- Tissue culture Rinderpest Vaccine (TCRPV) @1ml SC every alternative year, it can be given to all animals.
- Freeze dried goat tissue vaccine (FDGTV) @1 ml SC once in a life. It should not be given in exotic and crossbred cattle, sheep and goats.

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# Indigenous Dog Breeds

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Indigenous Indian dog breeds represent a unique and valuable genetic resource shaped by centuries of natural selection and adaptation to diverse agro-climatic conditions. These breeds are characterized by remarkable resilience, strong disease resistance, and exceptional functional efficiency, making them highly suitable for Indian environments. Unlike many exotic breeds, indigenous dogs require minimal maintenance, possess high intelligence, and demonstrate excellent working abilities such as guarding, hunting, and herding. Breeds like Rajapalayam, Mudhol Hound, Chippiparai, Gaddi, and Changkhi exemplify region-specific adaptations and cultural significance. Despite their importance, these native breeds face a gradual decline due to increasing preference for foreign breeds and lack of structured conservation efforts. This chapter highlights the characteristics, utility, and need for preservation of indigenous Indian dog breeds to ensure sustainable canine management and conservation of genetic diversity.

## Introduction

India is home to a diverse range of indigenous dog breeds that have evolved over centuries under varied climatic and ecological conditions. These native breeds are well adapted to local environments, exhibiting remarkable resilience, intelligence, and functional efficiency. Traditionally used for guarding, hunting, and herding, they have played a significant role in rural livelihoods and community life. Compared to exotic breeds, indigenous dogs are genetically robust, climate-resilient, and functionally efficient, making them ideal for Indian conditions. They are especially valuable for rural livelihoods, security, and conservation of native genetic resources.

## Key General Characteristics of Indigenous Dogs

1. Adaptability: Well-adapted to the Indian climate (heat, humidity, cold)
2. Disease Resistance: Strong natural immunity compared to foreign breeds
3. Low Maintenance: Less grooming, simple diet

4. Intelligence: High survival instincts and learning ability
5. Working Ability: Excellent for guarding, hunting, and herding

India has a rich diversity of indigenous (native) dog breeds that are highly adapted to local climates, diseases, and working conditions. These breeds are generally hardy and intelligent, and require less maintenance than exotic breeds. As per the NBAGR Karnal, a total of 5 Dog breeds are registered in India, and many locally identified populations are present in India.

### 1. Rajapalayam Dog

Origin: Tamil Nadu

Type: Sighthound / Guard dog

Characteristics:

- Strong, muscular, and tall (white coat)
- Excellent guard dog; very loyal to one owner



- Aggressive toward strangers
- Good hunting ability (used for wild boar)
- Low tolerance for other pets



## 2. Mudhol Hound (Caravan Hound)

Origin: Karnataka

Type: Sighthound

Characteristics:

- Slim, fast runner (greyhound-type body)
- Very high stamina
- Reserved and aloof temperament
- Needs open space for exercise
- Used for hunting and guarding



## 3. Chippiparai Dog

Origin: Tamil Nadu

Characteristics:

- Lean and athletic body
- Very fast and agile
- Excellent endurance in hot climate

- Loyal and intelligent and minimal grooming required



## 4. Gaddi Dog

Origin: Himanchal Pradesh

Characteristics:

- Used by shepherds for herd protection
- Large, powerful, and furry
- Highly loyal and protective
- Can fight predators like leopards



## 5. Changkhi Dog

Origin: Ladakh

Characteristics:

- It is a large, powerfully built breed, showcasing strength and alertness.
- Its broad head is framed by bushy fur around the neck and shoulders, resembling a lion's mane.
- Dark brown, sharp-set eyes reflect its intelligence and focus, while its triangular, drooping ears enhance its alert demeanour.



- Built for rugged terrains, it has strong legs and a bushy tail that curls slightly upwards or sideways,



### Conclusions-

Indigenous Indian dog breeds represent a valuable genetic resource shaped by natural selection and traditional practices over centuries. Their adaptability to diverse climatic conditions, strong disease resistance, and low maintenance requirements make them highly suitable for Indian environments, particularly in rural and semi-urban areas. Beyond their roles in guarding, hunting, and herding, these breeds contribute significantly to livelihood security and sustainable animal husbandry systems. However, increasing preference for exotic breeds and lack of organized breeding programs have led to the decline of several native breeds. Therefore, there is a pressing need for systematic conservation, selective breeding, and awareness programs to preserve these resilient and functionally efficient dogs. Promoting indigenous breeds will not only safeguard biodiversity and genetic heritage but also

support economical and sustainable canine management practices in India.

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# From soil to plate: How heavy metals enter our food

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Heavy metal contamination in agricultural ecosystems has emerged as a major concern for food safety, environmental sustainability, and human health. Toxic metals such as lead, cadmium, arsenic, mercury, and chromium can accumulate in soils through industrial activities, improper waste disposal, contaminated irrigation water, and intensive agricultural practices. These metals are absorbed by plants and transferred through the food chain, eventually reaching human diets. Long-term exposure to heavy metals through contaminated food may cause serious health problems, including kidney damage, neurological disorders, developmental issues, and increased cancer risk. Understanding the pathways of heavy metal movement from soil to plants and adopting effective management strategies are essential for reducing contamination. Sustainable soil management, regular monitoring, bioremediation approaches, and responsible agricultural practices can help minimize risks and ensure safer food production. Protecting soil health is the first step towards protecting human health.

## Introduction

Food is the foundation of human health, providing the nutrients needed for growth, development, and well-being. Most people associate fresh fruits, vegetables, cereals, and pulses with healthy eating, assuming that these foods are naturally safe and nutritious. However, an often-overlooked concern is the presence of heavy metals in the food we consume. Unlike harmful microbes that can be destroyed by cooking, heavy metals are non-biodegradable and can persist in the environment for decades. Once they enter agricultural soils, they can be absorbed by plants, transferred into edible plant parts, and eventually reach our dining tables through the food chain. This silent movement of toxic metals from soil to plate has become an emerging global concern for food safety, environmental sustainability, and public health (Rai *et al.*, 2019).

Heavy metals such as lead (Pb), cadmium (Cd), arsenic (As), mercury (Hg), chromium (Cr), and nickel (Ni) occur naturally in the Earth's crust. In

small quantities, some metals like zinc (Zn), copper (Cu), iron (Fe), and manganese (Mn) are essential for normal plant and human growth. However, excessive accumulation of these elements, along with toxic heavy metals, can pose serious risks to both crops and consumers. Rapid industrialization, mining activities, excessive use of chemical fertilizers and pesticides, disposal of untreated industrial effluents, sewage irrigation, and atmospheric pollution have significantly increased heavy metal concentrations in agricultural lands (Edelstein and Ben-Hur, 2018). As farming areas continue to expand near industries and urban settlements, the possibility of food contamination is becoming increasingly important.

Plants absorb water and nutrients through their roots, but they cannot always distinguish between beneficial nutrients and harmful heavy metals. As a result, toxic metals present in contaminated soils or irrigation water are taken up by plant roots and transported to leaves, fruits, grains, and other edible parts. Continuous consumption of contaminated food





may not produce immediate symptoms, but long-term exposure can lead to the gradual accumulation of heavy metals in the human body (Scutarașu and Trincă, 2023). Such accumulation has been associated with kidney and liver damage, nervous system disorders, weakened immunity, developmental problems in children, and an increased risk of certain cancers. Because these health effects develop slowly over time, heavy metal contamination is often referred to as a 'silent threat.'

Ensuring safe food production therefore requires more than increasing crop yields; it also demands maintaining healthy soils and preventing contamination throughout the agricultural system. Farmers, researchers, policymakers, and consumers all have important roles in reducing the movement of heavy metals into the food chain. Understanding how these contaminants enter agricultural soils, how plants absorb them, and what measures can effectively reduce their uptake is essential for protecting both environmental quality and human health. By increasing awareness and adopting sustainable farming practices, we can work towards producing food that is not only abundant but also safe for present and future generations.

### **Where do heavy metals come from?**

Heavy metals are naturally present in the Earth's crust and occur in soils in small amounts. Some metals such as iron (Fe), zinc (Zn), copper (Cu), and manganese (Mn) are essential for plant growth and human health. However, when their concentration increases beyond safe limits, they become harmful to plants, animals, and humans. Toxic metals such as lead (Pb), cadmium (Cd), arsenic (As), mercury (Hg), and chromium (Cr) are major concerns because they can persist in the environment for long periods.

Human activities have significantly increased heavy metal contamination in agricultural ecosystems. Industrial discharge, mining activities, improper waste disposal, and urban pollution are some of the

major sources. Wastewater from industries such as metal processing, battery manufacturing, textile, and chemical industries may contain high levels of toxic metals. When untreated wastewater is used for irrigation, these metals gradually accumulate in agricultural soils (Konappan *et al.*, 2025). Agricultural practices can also contribute to this problem. Continuous and excessive use of phosphate fertilizers may introduce cadmium into soils, while some pesticides and soil amendments may contain traces of heavy metals. Atmospheric pollution from industries, vehicles, and power plants also deposits metal particles onto agricultural fields. Over time, these contaminants build up in soils and create a pathway for their entry into the food chain.

### **The Journey of Heavy Metals from Soil to Plants**

Plants absorb water and nutrients from soil through their roots. However, they cannot always distinguish between beneficial nutrients and harmful metals. Because some toxic metals have chemical similarities with essential elements, plants may accidentally absorb them along with nutrients.

After entering plant roots, heavy metals can move to different plant parts, including leaves, stems, fruits, and seeds. The level of accumulation depends on the crop type, soil properties, and environmental conditions. Leafy vegetables such as spinach and coriander may accumulate higher levels of certain metals because of their large surface area and rapid growth. Root crops like carrot and potato can store metals in underground parts, while cereals such as rice and wheat may transfer metals into grains under contaminated conditions.

Soil characteristics strongly influence metal uptake by plants. Acidic soils generally increase the availability of heavy metals, making them easier for plants to absorb. In contrast, soils rich in organic matter can bind metals and reduce their movement into plants (Zwolak *et al.*, 2019). Therefore, maintaining healthy soil conditions is an important



strategy for reducing contamination. The problem does not end at crop harvest. When humans consume contaminated vegetables, grains, fruits, or animal products from contaminated sources, heavy metals enter the human body. Since these metals do not break down naturally, repeated exposure can lead to their accumulation over time.

### **Impact of heavy metals on human health**

Heavy metals are often called ‘silent pollutants’ because their harmful effects may appear only after long-term exposure. Unlike microbial contamination, heavy metals cannot be removed by cooking or simple food processing (Jomová *et al.*, 2024). Once they enter the body, they may accumulate in vital organs and interfere with normal biological functions.

Lead exposure is particularly dangerous for children because it can affect brain development, learning ability, and behaviour. In adults, prolonged exposure may cause kidney problems and cardiovascular disorders. Cadmium mainly affects the kidneys and bones and has been linked with bone weakening and increased cancer risk. Arsenic contamination through food and water can lead to skin problems, cardiovascular diseases, and several types of cancer. Mercury is known for its harmful effects on the nervous system and can affect brain development, especially in unborn children. Although some metals are essential for life, excessive intake can also become harmful. For example, zinc and copper are required for plant growth and human health, but high levels can disturb normal metabolic processes. Therefore, maintaining a proper balance of mineral elements is essential for both crop productivity and human well-being.

### **Protecting our food from heavy metal contamination**

Reducing heavy metal contamination requires combined efforts from farmers, industries, researchers, policymakers, and consumers.

Preventing pollution at the source is the most effective approach. Industries must properly treat wastewater before discharge, and strict regulations are needed to control hazardous waste disposal.

Farmers can reduce heavy metal uptake by adopting sustainable soil management practices. Adding organic matter, compost, and biochar can improve soil quality and reduce metal availability. Maintaining proper soil pH, avoiding excessive fertilizer application, and using clean irrigation water are important steps to produce safer crops (Surya *et al.*, 2025). Selecting crop varieties with lower metal accumulation ability can also help minimize risks. Modern scientific approaches such as phytoremediation, where specific plants are used to remove contaminants from polluted soils, and the use of beneficial soil microorganisms are promising methods for managing heavy metal pollution. Regular testing of soil, water, and agricultural products is also essential for early detection and prevention.

Consumers can contribute by washing vegetables properly to remove surface contaminants, maintaining a diverse diet, and choosing food produced from safe agricultural systems. While individual actions cannot completely eliminate the problem, awareness and responsible choices can reduce exposure. The journey of heavy metals from soil to plate reminds us that food safety begins long before food reaches our kitchen. Protecting soil health, adopting sustainable farming practices, and preventing environmental pollution are essential steps towards producing safe and nutritious food. A healthy plate begins with a healthy soil.

### **Future Prospects**

The future management of heavy metal contamination requires a combination of advanced technologies, sustainable farming practices, and effective environmental policies. Developing crop varieties with low heavy metal uptake, improving



soil remediation techniques, and promoting the use of beneficial microorganisms can help reduce the transfer of toxic metals into the food chain. Emerging approaches such as nanotechnology, biochar application, precision agriculture, and rapid soil and food monitoring tools offer promising solutions for early detection and management. Strengthening regulations on industrial waste disposal and encouraging farmers to adopt eco-friendly practices will be essential to ensure safe food production and protect human health in the coming years.

## Conclusion

Heavy metal contamination represents a hidden but serious challenge that connects soil health, crop safety, and human well-being. The journey of these toxic elements from contaminated soils to our plates highlights the importance of maintaining clean agricultural ecosystems. Preventing pollution at the source, adopting sustainable farming methods, and increasing awareness among farmers and consumers are key steps towards reducing risks. Protecting our soils today is essential for producing safe food and securing a healthier future for generations to come.

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## Pet Parasite Management: Commonly Asked Questions

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Pet parasites pose a significant threat to the health and well-being of companion animals as well as humans. This chapter addresses commonly asked questions related to parasite occurrence, risks, prevention, and management in pets. Parasites such as fleas, ticks, mites, and worms can infest both indoor and outdoor animals, causing a wide range of clinical problems from mild irritation to severe, life-threatening diseases. Many of these parasites also have zoonotic potential, making their control essential for public health. The chapter highlights the increasing risk of parasitic diseases due to factors such as climate change, animal movement, and environmental exposure. Effective parasite management relies on a combination of preventive strategies, including the use of parasiticides, regular diagnostic testing, and veterinary consultation. Emphasis is placed on year-round prevention, responsible product use, and adherence to regulatory guidelines to ensure safety and efficacy. Overall, the chapter underscores the importance of integrated parasite control programs to safeguard animal health, reduce zoonotic risks, and promote a healthier environment for both pets and humans.

### Introduction

Parasite occurrence is a common and often underestimated concern in companion animals, as even pets that spend most of their time indoors remain susceptible to infestations by fleas, ticks, and worms. If left untreated, these parasites can lead to severe health complications, causing significant discomfort, pain, and even life-threatening illnesses.

### A) Fundamentals of Pet Parasites

**What are pet parasites, and what effects do they have on animals?**

**“Organisms that feed on pets and cause discomfort, agony, and illness include fleas, ticks, mites, and worms. Parasites are a problem in almost every part of the world, can live inside or on our pets, and can endanger people who are close by”.**

While the animal suffers, parasites reside within or on the host's body, exploiting the host's metabolic

resources. Internal parasites like worms reside inside the body, whereas external parasites like fleas and ticks live on an animal's skin or concealed in its fur. While external parasites can cause skin irritation, bites, and hair loss, internal parasites frequently cause appetite loss, diarrhea, and excessive weariness. When external parasites are present, animals may frequently itch, which can exacerbate skin conditions and result in bleeding and blisters. Additionally, ticks and other parasites frequently act as "vectors." This implies that they have the ability to bite an animal and spread a disease. Pet owners are at danger because some parasites can infect both humans and animals. There are parasites practically everywhere in the planet. A pet may suffer greatly if parasite treatment is postponed rather than preventing an infection or infestation. For pets in high-risk areas, preventive is therefore usually advised.



**(ii) *Are pets prone to parasites?***

**“According to research, even pets who spend most of their time indoors are susceptible to parasite infections”.**

For example, a recent study showed that at least one dog tested positive for intestinal parasites in 85% of the places examined. Additionally, one diseased pet puts others at risk because parasites thrive on finding new "host-animals."

**(iii) *Why does preventing parasites in pets protect humans as well?***

**“Many of the parasites that infect or cause disease in animals also affect humans. In actuality, there is a moderate or high zoonotic risk for humans from more than half of the major parasite affecting dogs and cats. For this reason, preventing parasites in animals protects those in their immediate vicinity”.**

Certain parasites that cause harm to pets can also infect or infest humans. It can take at least three months to get rid of a flea infestation in a home. There is a direct correlation between tick-borne diseases in dogs and human cases in a given area, demonstrating how these parasites can spread from animals to humans.<sup>6</sup> Unintentional contact with animal excrement or a "shared environment" with pets, such as a garden or sandbox, can also expose humans to internal parasites like tapeworms. An infection with a parasite disease like toxocariasis can have serious long-term health effects in "at-risk" populations including the elderly, children, or immunocompromised people, while a toxoplasmosis infection in a pregnant woman can harm the foetus. Therefore, preventing parasites is crucial to shielding the local family, community, and general public from these possible "zoonotic" transmissions.

**(iv) *Is the threat posed by parasites increasing or evolving?***

**“Yes. Climate change makes it possible for parasites and vector-borne illnesses to flourish in previously uninhabitable locations”.**

Leishmaniosis is a deadly parasite illness. An infected animal may experience joint and muscular pain, renal failure, or even death. It can also transmit from an animal to humans and result in serious illness because it is a "zoonotic" infection. Researchers are witnessing a number of parasitic diseases, including leishmaniosis, migrate further north as climate change makes areas more favorable. In the past, leishmaniosis was limited to Mediterranean nations. Additionally, traveling facilitates spread the parasites into new regions. According to research conducted in the UK, dog travel from countries like France, Spain, and Cyprus is directly linked to the introduction of new tick species. Some veterinary organizations are being prompted by these findings to alert pet owners to the dangers of parasites. For example, the "risk for parasitic diseases continues to increase and expand into areas that have had historically low prevalence," according to the Companion Animal Parasite Council's most recent annual "Pet Parasite Forecast."

**B) *How Do You Manage Parasites?*****1. *How can pet owners prevent parasites from infecting their animals?***

**“Experts concur that prevention which frequently uses parasiticides and diagnostics is the greatest defense against parasites. These instruments are capable of identifying, monitoring, preventing, and treating the parasites that endanger animals. Each pet owner should collaborate with their veterinarian to create a plan that makes the most use of these resources”.**

Parasiticides are medications used to treat and prevent pet-harming parasites. These can be administered as injections, pills, collars, or spot treatments. While some parasiticides will offer combination protection against multiple types of parasites, others may only cure one. Instead of using





the term "parasiticide," many pet owners may refer to these medications by a brand name or a phrase like "flea collar." Even though parasiticides can successfully stop a parasite infestation, no medication is 100% effective, and owners might not always adhere to prescribed dosage regimens. Diagnostics are crucial in this situation. Diagnostics can check for parasites and make sure a preventative plan is offering strong defence. Frequent diagnostics aid in the early detection of these diseases so that they can be treated more successfully and prevent the sickness from spreading to other people. Additionally, diagnostics offer a crucial tool for tracking parasites. Researchers monitor parasite numbers and assist individuals in at-risk areas in putting effective preventive measures into place by 1. combining test findings from millions of animals.

### 2. *Do parasites require year-round preventive measures?*

**"All pets can benefit from a thorough parasite prevention strategy, even though the specific instruments may vary. The animal and those around it are best protected against parasites and vector-borne illnesses by methods that prevent infections in the first place".**

Owners should collaborate with their veterinarian or experts to develop a customized strategy, but it's crucial to understand that parasites are always present and that no animal not even those kept indoors is "risk free." For all pets, prevention should be a constant, lifelong concern. An assessment by a veterinarian can consider factors such as lifestyle, the local area, travel habits, and parasites prevalence. For example, ongoing parasiticide treatment together with yearly diagnostic testing is frequently advised in an area where heartworm is prevalent in order to prevent a potentially fatal infection.

### 3. *Can parasites be managed without the use of diagnostics or parasiticides?*

**"A scientifically validated method that significantly reduces the risk of infection is parasite control based on the use of parasiticides and thorough diagnostic tests".**

The Companion Animal Parasite Council (CAPC) advises yearly diagnostic testing for tick-transmitted diseases and heartworm. Additionally, CAPC supports "every pet, all year long," which refers to "year-round broad-spectrum parasite control with efficacy against heartworm, intestinal parasites, fleas, and ticks." Visit your veterinarian to learn more about effective parasite control.

### C) Regulations Regarding Parasiticide

**How are parasiticides controlled to guarantee the efficacy and safety of products?**

**"National agencies govern the assessment and approval procedure for parasiticides. Regulators have evaluated every approved medication for product quality, efficacy, and environmental, animal, and administer safety".**

Regulators demand that producers prove three essential components before any veterinary medication can be sold: product quality and consistency; efficacy; and safety for the animal, the person delivering it, and the environment. This includes testing to see how the product behaves in various scenarios, including handling it, administering it to an animal, bathing it after use, and more. Only until a regulatory body examines data from a manufacturer and determines that the advantages of the product exceed any risks will a "marketing authorization" be issued. Regulators may also advise producers to implement safety precautions or child-resistant packaging in order to reduce any residual dangers. Additionally, after a product is put on the market, it is monitored by "pharmacovigilance" systems, which allow regulatory bodies to keep tabs on and look into any reports of problems, including environmental problems brought on by the usage of veterinary medications. To make sure their products are safe and



effective, companies keep an eye on them from the moment they are sold until they are taken off the market.

2. ***How are any possible effects of parasiticides on the environment controlled?***

**“According to current regulations, there is little chance that veterinary medications for pets will have an adverse effect on the environment. Following product labels is a crucial part of the additional precautions that are in place to assist, address any possible routes to the environment”.**

According to current global recommendations, veterinary medications for pets have a low environmental risk because they are often used in modest amounts as specific treatments. Any possible pathways for veterinary medications to enter the environment can also be addressed by current precautions and mitigation techniques. For example, topical parasiticides are made to stay on animals since they are essential for their protection. Testing is frequently done to ensure that products have a minimal "wash off" when used as directed by the manufacturer. Products may also offer precautions that owners can follow to further lower any risk, like waiting a certain amount of time after application before giving an animal a bath. For all pet owners, reading product labels is crucial because they offer precise guidance on how to use a product safely and effectively.

## Conclusion

Parasite management is a critical component of responsible pet ownership, as parasites can adversely affect both animal and human health. Despite common misconceptions; all pets, including those kept indoors are at risk of parasitic infestations. The presence of parasites not only causes discomfort and disease in animals but also contributes to the transmission of zoonotic infections to humans. An effective parasite control program requires a proactive and integrated approach involving regular use of parasiticides, routine diagnostic testing, and continuous veterinary guidance. Year-round prevention is essential, as parasite risks persist across seasons and environments, further intensified by factors such as climate change and increased mobility of pets. Regulatory frameworks ensure that parasiticides are safe and effective, but their success depends on proper usage and adherence to guidelines by pet owners. Ultimately, raising awareness and promoting preventive strategies are key to minimizing parasite-related risks. By adopting a One Health approach that considers the interconnected health of animals, humans, and the environment, parasite management can significantly contribute to improved public health, enhanced animal welfare, and a safer living environment for all.

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## Germplasm conservation- a strategy for sustainable agriculture and future breeding

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Germplasm constitutes the genetic foundation of crop diversity and includes landraces, crop wild relatives, obsolete and modern cultivars, and advanced breeding lines. The widespread adoption of high-yielding varieties, monoculture, habitat degradation, and climate change has accelerated genetic erosion, making germplasm conservation essential for sustainable agriculture. Both in situ and ex situ conservation approaches safeguard valuable genetic resources and ensure their availability for future crop improvement. Conserved germplasm contributes to broadening the genetic base, development of high-yielding, climate-resilient and pest- and disease-resistant crops, biofortification, restoration of valuable traits, biotechnology, regenerative agriculture, and crop diversification. Institutions such as ICAR-NBPGR play a major role in systematic conservation, while farmers and community seed conservators preserve indigenous varieties and associated traditional knowledge. Integrating scientific conservation with farmer participation can protect crop genetic diversity, strengthen ecological resilience, and contribute to long-term food, nutritional, and ethical security.

Agriculture is the practice of the humanity which involves the cultivation and production of different crops according to the market needs. From the ancient times the crops are grown and successively evolved according to the growing environment, land type and selection which results in the development of so many species and its varieties for a particular crop which have its adhered qualities. These species are known as Landraces (locally adapted variety), Crop Wild Relatives (wild and semi-natural plant species of a crop), Obsolete cultivars (old commercial varieties), Modern cultivars (new high-yielding commercial cultivars) and Advanced Breeding Lines (elite lines having special breeding traits), which collectively known as Plant Genetic Resources or PGRs. These are the crop varieties which have the hereditary materials and used as the physical basis of heredity and are termed as Germplasm.

In previous landscape every region is specified with their local varieties and accounts in large collection of germplasm each having specific traits and qualities. After the Green revolution the major shifts bends towards the high production hence

introduction of high-yielding cultivars begins in large areas replacing these landraces and leads to genetic erosion or loss of germplasm.

The germplasm conservation is the practice of safeguarding the genetic information of these landraces or endangered plant species from extinction and for the purpose of the nutritional security and utilizing it in other breeding objectives for the development of the desired new crops. The conservation provides the ecological balance and ethical nutritional security. There are many ways to protect these PGRs which can be in-situ conservation practice and ex-situ conservation practice.

The in-situ practice mainly deals with the conservation and maintenance of resources in its natural grown habitat and ecosystem. This system maintained its adaptability in the changing environment and genetic traits can be maintained in the fields along with the cultivable areas.

Whereas the ex-situ is the conservation practice which mainly deals with the conserving of the heredity material such as seeds, pollens, vegetative



propagules in the seed or gene banks outside its natural habitat. For this seed banks and field banks are made, cryopreservation and micropropagation techniques is used for the collection of hereditary materials or germplasms and collection of the specimens occur.

### **Need for Germplasm Conservation**

The germplasm is the principle material in the breeding procedure for the development of the new crops for the nutritional security and ecological balance, so some of its needs are as follows;

- To protect the important local or farmer varieties or landraces from genetic erosions.
- To conserve the culturally and theological rich important varieties from extinction.
- Many varieties are utilized for the distinct social and economic activities used in production of different valuable items such as perfumes, artifacts, etc.
- Monoculture of agriculture and deforestation leads to endangerment of many valuable varieties which is the major need for protection.
- To maintain the stability of natural ecosystem and bio-diversity of plants in their specific regions.
- For the preservation of the specific important traits for the rich or broader gene pool.

### **Application of Germplasm conservation**

#### **❖ Broadening the genetic bases**

Germplasm conservation leads to maintenance of the genetic diversity of the PGRs which results in the high genetic combinations with new alleles and their traits. This decreases the genetic vulnerability and maintain high diversity among the species. This act as the reservoir of the genes.

#### **❖ Development of Improved yield varieties**

Through the information of the germplasm useful and economical traits can be incorporated in the crop for developing high yield varieties. This can be achieved through backcrossing and various other breeding methods.

#### **❖ Development of Pest- and Disease-Resistant Crops**

The landraces and crop wild relatives are highly resistant to the pathogenic biotic organisms such as fungus, bacteria and insects due to its rich genetic composition and natural selection which can be utilized in the creation of tolerant and susceptible varieties,

#### **❖ Creation of ideotype**

These are of intense use in the plant architecture for the concept of developing elite crop which gives benefits to the cultivator by incorporating superior gene accessions from the germplasm to enhance its productivity.

#### **❖ Restoration of agricultural traits**

Some useful traits may be reduced or lost during domestication and intensive agriculture. Conserved landraces, old cultivars and wild relatives act as genetic archives from which traits such as flavour, quality, local adaptation and stress tolerance can be recovered.

#### **❖ Biofortification and nutritional improvement**

Germplasm collections exhibit considerable genetic variation in micronutrients, proteins, vitamins, carotenoids and other health-promoting compounds. Nutrient-rich traits can be identified and used for developing biofortified cultivars. Example, Wild rice rich in antioxidants.



### ❖ Applications in Biotechnology

Germplasms provide diverse genetic bases for the biotechnological procedures and applications such as molecular-marker analysis, genomic selection, tissue culture and genome-editing research. The genome analysis can also help in better understanding of the genetic combinations and relations.

### ❖ Climate-resilient crops production

Landraces and crop wild relatives evolved and adapted to extreme environments provide genes for tolerance to drought, heat, salinity, flooding and other abiotic stresses. Conserving these genetic resources ensures that such adaptive traits remain available for breeding. For biotechnology

### ❖ Supporting regenerative agriculture

Germplasm adapted to local and low-input environments can provide useful traits such as improved physiological characters, efficient nutrient usage, improved root architecture and tolerance to marginal soils, etc. these traits thus minimize external inputs and maintain productivity.

### ❖ Ecological balance and crop diversification

Monoculture and HYVs are highly nutrient exhaustive and intensive which causes soil ecological balance. These conserved genetic resources are well adapted to its growing habitat and supports the more resilient agroecosystem, diversified crop rotations and intercropping.

### Role of institutes and farmers in Germplasm Conservation

Institutes like ICAR-NBPGR is the prime institutes which regulates in the conservation of the germplasm. The ICAR-NBPGR acts as an important and nodal institute for the management of PGR under the national agricultural research system. The Bureau's activities include PGR exploration, collection, exchange, characterization, evaluation,

conservation, documentation and its utilization. They are responsible for the quarantine of all imported PGR for the research purpose and have 10 regional stations located in different agro-climatic zones of India. It also has National Genebank which conserved 0.40 million accessions in its developed seed and field genebanks, cryo-banks and in-vitro genebank. It created many mobile applications for the purpose of documentation of the PGR which include NBPGR-PDS (Digital Passport Datasheet, for collection), 'Genebanks' and 'PGR Map' (for the indigenous collection).

**Farmers** participation also makes the Germplasm collections become more by direct involvement in evaluation and selection. Farmers may identify characteristics that are overlooked in conventional experimental programmes, including cooking quality, fodder value, storage ability, taste, maturity and suitability for local management practices.

Many progressive farmers have been practiced germplasm conservation measure which increases the plant genetic resources and ultimately benefitted themselves and the crop diversity. Some of the successful farmers are;

**Shri Sathyanarayana Beleri**, from Keralam awarded with the Padma Shri award for their initiative of making paddy gene bank by transforming his land and conserving 650 rare rice varieties by developing unique polybag cultivation technique to grow and guard multiple varieties simultaneously without cross-pollination risks. Preserved critical landraces like *Chitteni*, *Kagga* (salinity-tolerant), *Suggi Kayame*, and *Gandhasala* (aromatic).

**Ms. Rahibai Soma Popere** from Maharashtra also awarded with prestigious padma award and notably called as seed mother who developed community-led bank and preserve 120 indigenous seed variety including native, climate-resilient varieties of hyacinth beans (*Vaul*), millets, wild vegetables, and





drought-resistant paddy. This is achieved by adopting traditional, low-cost organic preservation techniques using local mud and cow dung pots to save seeds.

**Rghupat Singh** who gave his law career to revive 55 endangered native crop and vegetable species mainly 22 varieties of rajma. He also trained a significant number of farmers in the seed conserving practices and its purification.

**Shri Babulal Dahiya** who tracked and identified the forgotten crop seeds by learning them about in ancient Bagheli folk songs and riddles and successfully collected, grew and preserved over 200 indigenous rice varieties organically. Also initiated Beej yatra to collect local plant varieties across his native state Madhya Pradesh.

**Ms. Sabarmatee and Shri Radhamohan**, father-daughter duo who practices ex-situ conservation by multiplying over 500 indigenous rice varieties and more than 80 rare seed pulses in a patch of barren wasteland in Odisha. They also signified the

importance of the ecological farming by demonstrating integration of eild germplasm for highly resilient against pest and climate change.

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# Dog: The Companion of Children, Lonely Individuals, Families, and Society

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Dogs have long been regarded as loyal companions, playing a significant role in enhancing human well-being across different sections of society. This article explores the multifaceted contributions of dogs to children, lonely individuals, families, and the broader community. For children, dogs foster emotional development, improve social skills, and encourage physical activity, thereby supporting both mental and physical health. Among lonely individuals, dogs provide companionship, reduce stress, and help alleviate conditions such as anxiety and depression by promoting a sense of purpose and routine. At the family level, dogs strengthen bonds, enhance security, and encourage healthier lifestyles through shared responsibilities and activities. In society, dogs act as social catalysts, facilitate community engagement, and serve important roles as service and therapy animals. Overall, dogs contribute significantly to emotional stability, physical health, and social cohesion. Recognizing their value underscores the importance of responsible dog ownership and maintaining canine health for the well-being of individuals and society at large.

## Introduction

Dogs have been known as man's best friend for centuries. Their loyalty, companionship, and unconditional love make them invaluable members of families and society. Healthy dog populations play the multifaceted roles in the lives of children, lonely individuals, families, and the broader community. This article focuses on these roles.

## Dogs and Children

- 1. Emotional Support and Development:** Dogs provide emotional stability and comfort to children. They help in developing empathy and responsibility. Interaction with dogs can reduce anxiety and stress in children.
- 2. Physical Activity and Health:** Dogs encourage children to engage in outdoor activities. Playing with dogs can improve physical health and reduce the risk of obesity.
- 3. Learning and Cognitive Development:** Dogs can assist in educational settings, helping children with reading and learning difficulties. They promote cognitive development through interactive play.
- 4. Unconditional Love and Companionship:** Dogs offer unwavering loyalty and affection, which can help children feel secure and loved. This bond can be especially comforting during stressful or lonely times.
- 5. Stress and Anxiety Reduction:** Interacting with dogs has been shown to lower cortisol levels and trigger the release of endorphins, the body's natural feel-good hormones. This can help reduce stress and anxiety in children.
- 6. Improved Social Skills:** Dogs can act as social catalysts, encouraging children to interact with others. Taking care of a dog teaches responsibility, empathy, and patience, which are crucial social skills.



7. **Emotional Support:** Dogs can sense and respond to human emotions, providing a calming presence that helps children feel more at ease. This can be particularly beneficial for children who have experienced trauma or have anxiety.
8. **Routine and Responsibility:** Caring for a dog involves daily routines, which can provide structure and a sense of purpose for children. This responsibility can boost their self-esteem and confidence.

### Dogs and Lonely Individuals

1. **Companionship and Emotional Support:** Dogs offer constant companionship, which can be especially beneficial for individuals living alone. They can sense their owners' moods and often provide comfort during times of distress. This emotional support can be crucial for managing mental health conditions. They provide a sense of security, purpose and routine.
2. **Mental Health Benefits:** Interacting with dogs can lower stress levels by reducing cortisol (the stress hormone) and increasing serotonin and dopamine, which promote feelings of happiness and well-being.
3. **Alleviating Depression and Anxiety:** Dogs provide companionship and unconditional love, which can help alleviate symptoms of depression and anxiety. Their presence can offer comfort and a sense of purpose. Simply spending time with a dog can elevate mood and provide a sense of joy and fulfilment. The act of caring for a dog can also instil a sense of responsibility and achievement.

### Dogs and Society

1. **Enhanced Social Interaction:** Walking a dog often leads to increased social interactions with other dog owners and people in the community. This can help reduce feelings of isolation and build a sense of community. Dogs can act as social

catalysts, helping lonely individuals make new friends.

2. **Community Engagement:** Dogs can play a role in community events and activities, fostering a sense of togetherness and social cohesion. They can help in community policing and search and rescue operations.
3. **Cultural Significance:** Dogs hold a special place in various cultures and traditions. They are often featured in literature, art, and media, symbolizing loyalty and friendship.
4. **Service and Therapy Dogs:** Dogs assist individuals with disabilities, providing essential services. Therapy dogs visit hospitals, schools, and nursing homes, offering comfort and support to those in need. Their presence can improve the emotional well-being of patients and residents. Similarly, training your dog to be an emotional support animal can be a rewarding experience that strengthens your bond and enhances your well-being.
5. **Active Lifestyle:** Older adults with dogs are more likely to maintain an active lifestyle, which can help prevent age-related health issues and improve overall quality of life.

### Dogs and Families

1. **Strengthening Family Bonds:** Dogs bring families together through shared activities and responsibilities. They teach children about teamwork and cooperation.
2. **Security and Protection:** Dogs provide a sense of security and protection for families. They can alert family members to potential dangers.

**Health and Wellness:** Dogs can help reduce stress and improve the overall mood of family members and lead to a more active lifestyle for the entire family. Dog owners are more likely to engage in regular physical activities such as walking, jogging,



and playing with their pets. This helps improve cardiovascular health, reduce obesity, and enhance overall fitness. One study showed dog owners who walk their dogs regularly may face one-third the risk of diabetes of those who don't own a dog. Studies have shown that dog owners have a lower risk of heart disease. The physical activity associated with dog ownership, along with the stress-reducing effects of pet companionship, contributes to better heart health. Owning a dog may reduce your risk of dying from a heart attack or stroke by 31%. There was a link between people with prior heart events who had a dog living at home with a 65% reduced risk of death. Studies suggest that dog owners may experience improved longevity due to the combined physical, mental, and social benefits of dog ownership.

### ***Conclusion***

Dogs are more than just pets; they are integral members of our lives and society. Their roles as companions to children, lonely individuals, families, and the broader community highlight their importance. By promoting regular physical activity, reducing stress, enhancing social interactions, and providing emotional support, dogs play a vital role in

fostering healthier lives. Understanding and appreciating the diverse ways dogs contribute to our well-being; we can foster stronger bonds with these loyal companions. Therefore, the responsibility of the owner and society to maintain the health of dogs is of prime importance to keep families and societies to be healthy.

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## Soil fertility status of RLBCAU farm at Jhansi

Abhishek kumar Shukla, Adima Bharadwaj, Sandeep Upadhya

Soil is the uppermost layer of variable depth of the earth consisting of loose material, which is the main support for natural vegetation and other life forms of our planet. Soil is an independent dynamic body of nature that acquires properties in accordance with the forces which act upon it. The important soil forming factors such as parent material, climate, relief, organism and time have direct impact on soil properties. The soil forming processes as oxidation, reduction, eluviation and illuviation are related to soil solution and further on stages of soil development crop yield is a function of many factors in which soil fertility is an important one and must be periodically monitored due to continuous crop removal of plant nutrients. In order to achieve higher productivity and profitability, it should be realized that fertility levels are periodically monitored to ensure balanced nutrition for high production level and soil health maintenance. The other trace elements like Fe, Cu, Mn and B may be sufficient for low to medium production level but may start limiting the crop growth at high level of crop production. The optimum crop yield can only be achieved when high yielding crop varieties are properly nourished i.e. all limiting nutrients are provided in correct amount and proper ratio. The use of plant nutrients in a balanced proportion is the prime factor for efficient fertilizer program. Balanced nutrient use ensures high production level and helps to maintain the soil health. Use of optimum dose of fertilizer in the agricultural field is the most important agricultural input for increasing crop production. Soil testing is now considered as an important tool for the recommendation of the fertilizers doses for various crops in India. The application of fertilizer on the basis of soil test will not only considerably reduce the cost of inputs for fixed targeted yields but also help in balanced fertilizer application that will lead to better soil health and sustainable production.

Bundelkhand is spread over about 69,000 sq. km. of land in seven districts of Uttar Pradesh (Chitrakut, Banda, Jhansi, Jalaun, Hamirpur, Mahoba and Lalitpur) and seven districts of Madhya Pradesh (Chhatarpur, Tikamgarh, Damoh, Sagar, Datia, Panna and newly added district is Niwari). The region falls under Central Plateau and Hills Agro-climatic Region. This region is amongst the most degraded ecosystems characterized by undulating and rugged topography, highly eroded and dissected land, poor soil fertility and low water holding capacity and scarce ground water resources. The 56% area of Bundelkhand region comes under the red soil (Alfisols and Entisols), which is characterized by coarse gravelly and light textured with poor water holding capacity. Therefore, establishment of woody perennials is very difficult without soil and water conservation measures, particularly in red soils of the

region. Remaining 44% area comes under black soil which is low lying and suffers from inadequate drainage, cracking and shrinking, and thus gives narrow time for soil working (CAFRI, 2018).

(KVK) The district Jhansi comes under Bundelkhand Agro climatic Zone (6) of Uttar Pradesh and located at latitude of 25° 27' North and longitude of 78° 37' East and is about 271 meter from msl having 5 sub divisions, 8 community blocks and 839 villages.

### 2. Soil types:

The soils of the Jhansi district are characterized by their varying depth, topographic situations and colours. The two main soil groups are red and black that generates four soil series locally known as rakar, parwa, kabar and mar. The soil texture varies from rocky, gravelly, sandy, sandy loam to clay loam and





having gentle to steep (0.5 to 10 %) slope with low to medium organic carbon content and very low to high water holding capacity. Farming situations and cropping patterns vary as per soil type, water, vegetation and livestock availability. The average annual rainfall of the district is 884.6 mm and 90 per cent received during the monsoon season. Droughts and long dry spells occur during rainy season is the common feature in the district which directly affect the kharif as well as rabi crop production.

(IGFRI) Tyagi et al. (1992-1993) reported that the grassland soils varied in textures viz., clay loam, sandy loam, sandy clay loam, sandy clay and loam. However the majority of the soils were clay loam. Soils are generally alkaline in reaction (pH 8.6-9.0). The soils of Bundelkhand in general were low particularly in terms of available N and P, varying in the range of 56.4 - 232.0 kg and 1.45- 8.51 kg/ha N

and P, respectively. Soils were rich in available K and 65 per cent soils had more than 280 kg K O/ha. The content of organic carbon was very low 2 (0.014) to low (0.568%) in the soil. Soil profile studies of red, black and calcareous soils indicated that the moisture content and loss on ignition increased with increasing depth in all the soil types. Mixed black and red soil had higher clay and silt sesquioxide percentage than red and calcareous soils. In black and red soils the accumulation of lime was higher in lower horizon whereas in calcareous soil, its distribution was nearly uniform (Tripathi, 1982).

These soils were classified in to three groups namely Bundelkhand Type-1 (Rakar), Bundelkhand Type-2 (Parwa) and Bundelkhand Type-3 (Kabar & Mar) as reported by Tripathi et al. (2003). These soils were described along with some of the important physical and chemical properties (Table)

| Soil properties                 | Type- I (Rakar) | Type- II (Parwa) | Type – III |         |
|---------------------------------|-----------------|------------------|------------|---------|
|                                 |                 |                  | Kabar      | Mar     |
| Soil Depth (cm)                 | < 50            | 50-100           | 100-120    | 120-150 |
| Field capacity (%)              | 10.50           | 14.50            | 19         | 26.50   |
| Wilting Point (%)               | 4.20            | 6.20             | 8.60       | 14      |
| Available soil Moisture (mm/cm) | 53              | 138              | 175        | 207     |
| Permeability (mm/hr)            | 40              | 20               | 10         | 6.0     |
| Available Nitrogen              | VL- L           | L-M              | L-M        | M       |
| Available Phosphorus            | VL-L            | L-M              | VL-L       | L       |
| Available Potassium             | L-M             | M- H             | M-H        | H       |
| Available Sulfur                | VL- L           | L-M              | L-M        | M       |

### Bundelkhand Soil Type-1

Locally, these soils are known as Rakar and are Entisols according to Soil Taxonomy (USDA,

1975). They are coarse grained, reddish brown in colour with low thickness of soil material. These soils were found both at elevated as well as the foothill areas. The pH ranged from 6.5 to 7.5 with low soluble



salts. Very low to low available N and P, low to medium potash and very low to low sulphur contents were tested in these soils. Field capacity, wilting point, available soil moisture and permeability of the soil were 10.5%, 4.2% and 53 mm/cm soil depth and 40 mm/hr, respectively. The soil productivity was reportedly very low due to excessive drainage, low soil depth, very low water retention capacity and low content of organic matter. Crust formation on the soil surface posed a very serious problem that impaired seed germination when rained just after sowing. Nitrogen, phosphorus and sulphur were the most deficient nutrients. These soils are fit for growing sorghum, cowpea, urd, moong, sesamum etc.



RAKAR (Entisol)

### Bundelkhand Soil Type-2

This group of soils measured 50-100 cm depth and the most important feature was the presence of calcium carbonate in the form of kankar layer at lower layers of the soil profile. The soil was locally described as Parwa and taxonomically belonged to Alfisols. The colour of the soils was brown, which is redder in shade. Texture varied from sandy loam to loam with slightly alkaline soil reaction ( $\text{pH} > 7.5$ ). These soils are well drained and more fertile than Bundelkhand Type-1, suitable for cultivation of all crops. These are low in organic matter, low to medium in available nitrogen, phosphorus and sulphur and medium to high in potash. The nutrient deficiency was in the order:  $\text{N} > \text{P} > \text{S}$ . Other physical

properties such as field capacity, wilting point, available soil moisture and permeability were 14.5%, 6.2%, 138 mm/cm and 20 mm/hr, respectively.



Parwa (Alfisol)

### Bundelkhand Soil Type-3

These soils were blackish in colour and heavy textured. No sharp colour distinction between the horizons was found. The soils, locally named as Kabar and Mar, which were grouped in Inceptisol and Vertisol orders, respectively. Generally they were present in low lying areas. The soils were deep with parent rock lying below 120-150 cm depth. The clay has characteristics with swell and shrink properties with higher moisture retention capacity compared to other types of soils in this region. Kabar soils were free from lime, clayey, coarse grained and develop cracks under dry conditions. On the other hand Mar soils were very fine textured clays, dark blackish in colour, deep (150 cm or above) with very high moisture retention capacity. The most important characteristic of Mar soils was the presence of calcium carbonate particularly in lower horizons with large and occasionally deep cracks on drying. They posed problems in the workability due to the shrink and swell characteristics of clay. Impeded drainage was an important feature, which was due to poor permeability. Kabar soils were low to medium in N, very low to low in P, medium to high in potash and low to medium in sulphur. The field capacity, wilting



point, available soil moisture and permeability of Kabar soils were 19%, 8.6%, 175mm/cm profile depth and 10mm/hr, respectively. The nutrient deficiency found was in the order of: N> P> S. Mar soils were medium in nitrogen and sulphur, low in phosphorus and high in potash. The field capacity, wilting point, available soil moisture and permeability were 26.5%, 14%, 207 mm/cm and 6 mm/hr, respectively. Phosphorus was the most deficient nutrient. Kabar soils are suitable for both kharif and rabi crops whereas Mar soils were suitable for growing only rabi crops with good management practices.



Mar (Vertisol)



Kabar (inceptisol)



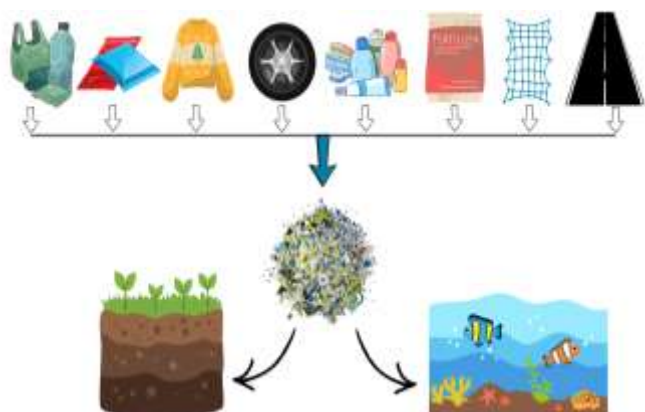
# Role of Microplastics in Soil Degradation and Water Contamination

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India, the world's third-largest plastic producer, generates 3.5 million tonnes of plastic waste annually, of which 60% remains uncollected (CPCB, 2022). This burden progressively degrades into microplastics particles below 5 mm, permeating agricultural soils, rivers, groundwater, and coastal zones at alarming concentrations. Studies document up to 25,000 particles/kg in Indo-Gangetic soils, 5,000–28,000 particles/L in the Ganga and Yamuna rivers (Napper et al., 2021), and microplastics in 78% of groundwater samples across multiple states (Tiwari et al., 2022). India's monsoon hydrology, intensive agriculture, open waste burning, and weak waste infrastructure together create a compounding environmental crisis that threatens food security, water quality, biodiversity, and public health, demanding urgent policy reform and sustained scientific investigation.

## 2. Introduction

Soil degradation encompassing loss of organic matter, structural collapse, nutrient depletion, and contamination that affects an estimated 16.35 million hectares in India annually (ICAR-NAAS, 2015). India ranks 120th of 122 nations in water quality indices (WQI, 2019), with industrial effluents, raw sewage, agricultural runoff, and emerging contaminants compounding pollution loads across its 14 major river systems and 141 million hectares of net cultivated area. Microplastics, defined as plastic particles between 1  $\mu\text{m}$  and 5 mm, now constitute a structurally pervasive category of contaminant that bridges both soil and aquatic degradation processes, interacting with and amplifying existing stressors.



Distribution of Micro Plastic in Soil and Water

India's microplastic crisis is inseparable from its plastic waste management failure. With a formal recycling rate of only 30% and widespread open dumping and burning, vast quantities of plastic freely enter open environments. The Ganga ranks among the world's top ten plastic-polluted rivers, transporting 0.12–0.24 million tonnes of plastic annually to the Bay of Bengal (Meijer et al., 2021). Microplastic concentrations in the Ganga at Varanasi reach 5,000–28,000 particles/L, exceeding most European rivers by an order of magnitude. Atmospheric microplastic fallout in Indian cities reaches 1,200–8,600 particles/m<sup>2</sup>/day (Singh et al., 2023), over 20 times the rates recorded in remote European mountain areas (Allen et al., 2019). Intense monsoon rainfall then mobilizes these deposits in powerful seasonal pulses into rivers, wetlands, and groundwater recharge zones.

## 3. Sources and Pathways of Microplastics

### 3.1 Agricultural and Sewage Sources

India applies plastic mulch films which are predominantly LDPE, across 1.8 million hectares of farmland, leaving residue fragments accumulating at 20–180 kg/ha in Indo-Gangetic Plain fields after successive cultivation cycles (ICAR, 2020). Wastewater irrigation in peri-urban areas of Delhi,



Hyderabad, and Chennai deposits 1,800–11,000 microplastic particles/kg dry weight in topsoil (Kumar et al., 2020). Sludge from India's 1,152 Sewage Treatment Plants is routinely land-applied without any microplastic screening protocols, constituting a substantial and entirely unmonitored contamination pathway.

### 3.2 Industrial, Urban, and Atmospheric Sources

Textile manufacturing hubs in Tiruppur, Surat, and Ludhiana discharge 1,200–15,000 synthetic microfibers/L in industrial effluents before treatment (Sundarakrishnan et al., 2022). Informal plastic recycling clusters in Delhi NCR and Mumbai generate surrounding soil concentrations of 6,500–22,000 particles/kg (Verma et al., 2023). Leachate from India's 3,159 largely non-compliant dumpsites chronically contaminates adjacent soils and groundwater (CPCB, 2022). Lysimeter studies simulating Indian monsoon rainfall intensities found 12–18% of surface-applied microplastics reaching drainage water within a single monsoon season, substantially higher than temperate-region estimates due to India's intense rainfall events and high surface runoff (Gupta et al., 2022).

### 4. Physicochemical Properties

Indian environmental microplastics are dominated by polyethylene (28–45%), polypropylene (18–32%), polyester/PET (15–24%), and polystyrene (8–14%), reflecting the country's plastic consumption profile (Acharya et al., 2021). Fibers predominate in river samples (62–78%) while fragments dominate agricultural soils (54–68%), indicating differential source origins and transport pathways. India's intense solar radiation (6–7 kWh/m<sup>2</sup>/day) dramatically accelerates UV-induced surface oxidation of environmental microplastics, generating carbonyl and hydroxyl functional groups that markedly enhance adsorption of heavy metals prevalent in India's industrially affected soils. Microplastics from the Yamuna River in Delhi showed lead adsorption

capacities of 18–56 mg/g — far exceeding virgin polymer values (Sharma & Chatterjee, 2022). The plastisphere biofilm colonizing river microplastics harbours ESBL-resistant *E. coli* at 500–2,000 fold above background sediment concentrations, directly linking microplastic contamination to India's deepening antibiotic resistance crisis (Khatri et al., 2023).

## 5. Mechanisms of Soil Degradation and Water Contamination

### 5.1 Soil Structure, Nutrients, and Climate Implications

LDPE microplastics at concentrations representative of intensively cultivated Punjabi fields (500–2,000 mg/kg) reduce soil aggregate stability by 18–35% and increase bulk density by 4–8% in alluvial Indo-Gangetic soils, impairing aeration and root penetration essential for wheat and paddy production (Kumar & Singh, 2021). Maharashtra's Black Soils (Vertisols) show accelerated pre-monsoon cracking and erosion under microplastic-induced disruption of swelling-shrinkage dynamics (Patil et al., 2022). At the nutrient level, soil urease activity declines 27% and phosphatase declines 31% in Tamil Nadu laterite soils contaminated with PS microplastics compounding the nutrient crisis of Indian soils averaging below 0.5% organic carbon nationally (Selvaraj et al., 2022). Studies in Indian paddy fields document 34–52% increases in N<sub>2</sub>O emissions, a greenhouse gas 265× more potent than CO<sub>2</sub> from microplastic-contaminated flooded soils, directly implicating microplastic pollution in India's climate feedback loop (Verma & Kumaraswamy, 2022).

### 5.2 Water Contamination and Contaminant Vector Role

The Yamuna River carries 15,000–27,500 microplastic particles/L during low-flow winter conditions, increasing turbidity and providing sorption surfaces for the heavy metals, dyes, and pharmaceutical compounds abundant in its waters





(Verma et al., 2022). Irrigation tanks in Telangana accumulate up to 45,000 particles/L, threatening the 25% of India's small-scale farming dependent on tank irrigation (Reddy et al., 2023). As contamination vectors, PE microplastics adsorb endosulfan, a legacy organochlorine pesticide in Punjab's cotton belt at concentrations 800–12,000 times those in surrounding soil water, mobilizing it to drainage channels and groundwater (Rani et al., 2021). Shallow groundwater wells across Rajasthan, Gujarat, and Tamil Nadu show microplastic contamination in 78% of samples at 0.4–12 particles/L a direct and growing threat to rural drinking water (Tiwari et al., 2022).

## 6. Impact on Soil and Water Biota

### 6.1 Microbial Communities and Soil Fauna

Indian soil microbiomes are critical for maintaining biological fertility across agroecosystems from Himalayan foothills to tropical deltas show pronounced sensitivity to microplastic contamination. PET microplastics reduce total bacterial count by 22–41%, suppress *Rhizobium* populations by 38%, and cut soil organic carbon (SOC) by 12–28% through impaired decomposition (Kumar & Singh, 2021). Total microbial populations of bacteria, fungi, and actinomycetes are decline by 15–35%, with mycorrhizal fungi disproportionately suppressed, weakening phosphorus acquisition. Microplastics also reduce macro-aggregate stability by 18–31% by disrupting microbially secreted extracellular polymeric substances (EPS), increasing vulnerability to monsoon erosion (Patil et al., 2022). Nutrient cycling is comprehensively disrupted the urease declines 27%, phosphatase 31%, and dehydrogenase up to 40% collectively impairing nitrogen mineralization, phosphorus release, and organic matter breakdown (Selvaraj et al., 2022). Earthworms in Maharashtra sugarcane soils show 24–46% reductions in cocoon production and immune suppression, further weakening faunal drivers of soil health (Pawar et al., 2022).

### 6.2 Aquatic Life and Plant–Soil Interactions

India's freshwater ecosystems already under severe stress from industrial effluents, sewage discharge, and over-abstraction, face a compounding threat from microplastic-induced alteration of fundamental water quality parameters. Dissolved oxygen (DO) drops by 1.2–2.8 mg/L in heavily contaminated water bodies, crossing the critical 4 mg/L fish survival threshold in already warm Indian surface waters (Reddy et al., 2023). Leaching of acidic plasticizers lowers water pH by 0.3–0.8 units in slow-moving tanks and irrigation channels, altering chemical speciation of co-contaminants (Verma et al., 2022). Chemical releases are equally alarming the Indian river microplastics leach BPA (0.5–18 µg/L), phthalates (2–45 µg/L), and nonylphenol (0.8–12 µg/L), all endocrine disruptors impairing fish and amphibian reproduction at sub-microgram concentrations (Sharma & Chatterjee, 2022). Commercially critical fish like *Labeo rohita* and *Catla catla*, carry 4–19 particles/individual with documented gut histopathology and hepatotoxicity (Sarkar et al., 2023), while Godavari mussels accumulate 180–640 particles/individual, concentrating chemical contaminants in food chains of rural communities (Sundar et al., 2022). Rice crops show 18–23% yield reductions and wheat 11–21% germination decline under field-realistic microplastic concentrations (Rao et al., 2022).



Impact of Micro Plastic on Soil and Water



## 7. Ecosystem Services, Soil–Water Interactions, and Synergistic Stressors

For India where agriculture employs 47% of the workforce and contributes 18% of GDP, the ecosystem service losses from microplastic contamination are severe and escalating. Yield losses are projected to cost ₹18,000–42,000 crore (USD 2.1–5.0 billion) annually by 2035 (Sharma et al., 2023). Contaminated soils lose 8–15% of potential carbon sequestration capacity, undermining India's Net Zero 2070 commitments, while N<sub>2</sub>O emissions from paddy soils add a direct climate feedback dimension. Coastal fisheries supporting 14.5 million fisherfolk face compound threats from fish health impairment and consumer rejection of products from visibly polluted water bodies. Over-exploited Indo-Gangetic aquifers are declining at 0.3–1.0 m/year, face accelerating microplastic infiltration through desiccation cracks, creating a long-term contamination legacy that current management frameworks cannot address. Synergistically, combined PE microplastic and chromium exposure in Punjab's industrial belt reduces soil microbial biomass carbon by 58%, nearly double the effect of Cr alone (Kaur et al., 2022). Under 2050 climate projections, microplastic-drought interactions are modeled to amplify rainfed crop yield losses by 20–35% in peninsular India compared to either stressor acting independently (Mishra et al., 2023).

## 8. Methodological Challenges and Research Gaps

Indian microplastic studies predominantly employ FTIR spectroscopy (65%), Raman spectroscopy (28%), and Nile Red fluorescence staining (42%) for polymer identification (Acharya et al., 2021). However, the absence of standardized national extraction protocols is a critical weakness for inter-laboratory analysis of identical Ganga sediment samples produced particle count variability of 180–420% (Singh et al., 2022), making data synthesis for regulatory purposes unreliable. Microplastics are entirely absent from CPCB and SPCB environmental

monitoring frameworks, with no regulatory thresholds established under Indian law, unlike heavy metals and conventional organic pollutants. The nanoplastic fraction (below 1 µm) remains virtually unstudied in India despite growing evidence of its superior biological penetrability and toxicity. India's spatial diversity encompassing 14 major river systems, 45 drainage basins, and vastly different agroecological zones demand sampling coverage that currently exceeds available national research funding, leaving large geographic and temporal gaps in the evidence base.

## 9. Mitigation Strategies and Management

### 9.1 Policy and Source Reduction

India's Plastic Waste Management Rules (amended 2022) banned single-use plastics below 75-micron thickness and established an Extended Producer Responsibility (EPR) framework mandating accountability for plastic packaging throughout its lifecycle. However, compliance in rural markets remains at only 40–65% (CSE, 2023), reflecting limited enforcement infrastructure. Incorporating standardized microplastic parameters into India's National Water Quality Monitoring Programme is covering 3,122 stations across 36 states that would generate the national baseline data essential for evidence-based threshold-setting and regulatory action. India's traditional agricultural practices are including crop residue mulching, jute matting, and coir-based products etc. are represent readily available biodegradable alternatives to plastic mulch films that warrant government incentive frameworks.

### 9.2 Remediation Technologies for the Indian Context

Bioremediation offers a culturally and economically appropriate pathway: IIT Delhi-isolated *Pseudomonas aeruginosa* strains from Mumbai landfill soils degrade LDPE at 6.4% weight loss per 30 days under optimized conditions (Skariyachan et al., 2021). Vetiver grass (*Chrysopogon zizanioides*)



which is native to India, stabilizes and concentrates microplastics in rhizosphere soil, preventing water transport while providing industrial fiber biomass (Thakur et al., 2022). Constructed wetlands piloted in Punjab and Kerala achieve 42–78% microplastic removal from agricultural drainage at low cost and are readily scalable for rural Indian contexts (Kumar et al., 2023). Magnetic separation technology evaluated in Surat's textile district achieves greater than 85% removal from industrial effluents at pilot scale (Rao & Sharma, 2023). Biodegradable PBAT mulch films achieve 94% soil degradation within 12 months under Indian field conditions, though their 2.5–3× cost premium over LDPE necessitates government subsidy frameworks to enable smallholder adoption (Patil & Joshi, 2022).

## 10. Future Directions and Research Priorities

India's microplastic research and governance agenda requires action across five interconnected priorities. First, long-term microplastic monitoring must be integrated into existing CPCB water quality infrastructure to establish national baselines and track temporal trends linked to monsoon dynamics and land-use change. Second, India-specific regulatory thresholds for soil and water microplastic concentrations must be developed through nationally representative studies, as European and North American standards do not reflect India's distinct polymer profiles, ambient temperatures, and co-contaminant burdens. Third, targeted investment in nanoplastic analytical infrastructure like dynamic light scattering, electron microscopy, and pyrolysis-GC/MS is essential at national research institutions to fill the current near-complete absence of sub-1 µm data. Fourth, interdisciplinary socioeconomic research is urgently needed to quantify livelihood impacts on smallholder farmers, fisherfolk, and rural water users are the most exposed and most vulnerable populations, to build the equity dimension into policy frameworks. Fifth, India should leverage its UN Global Plastics Treaty negotiating position to champion science-based, implementable

microplastic standards for developing nations, ensuring global governance frameworks are equitable and grounded in Southern scientific evidence.

## 11. Conclusion

India's microplastic contamination of soil and water is widespread, severe, and accelerating which is driven by plastic waste mismanagement at a scale reflecting systemic failures in waste infrastructure, regulatory enforcement, and producer accountability. The evidence reviewed herein is unambiguous: microplastics alter fundamental soil physical and chemical properties, suppress biological communities across trophic levels, impair yields of India's staple food crops, contaminate groundwater consumed by hundreds of millions, release toxic chemicals into aquatic systems, and amplify the transport and bioavailability of legacy co-contaminants which collectively threatening the food and water security of 1.4 billion people. India nonetheless possesses powerful assets to confront this crisis: an indigenous tradition of biodegradable material uses in agriculture, a large and growing scientific community with demonstrated bioremediation and materials innovation capability, and the demographic and economic weight to shape global plastic governance norms. Translating these assets into meaningful action requires mandatory microplastic monitoring in all national environmental programs, enforceable EPR frameworks with genuine corporate accountability, targeted government incentives for biodegradable agricultural inputs, and sustained investment in remediation technologies scaled to India's agroecological and socioeconomic reality. The microplastic crisis cannot be resolved without transforming the linear plastic economy into a circular one and protecting the soil and water commons on which Indian livelihoods, ecosystems, and future generations fundamentally depend.

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## Castor (*Ricinus communis* L.): A Multipurpose Industrial Oilseed Crop with Expanding Global Importance

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Castor (*Ricinus communis* L.), belonging to the family Euphorbiaceae, is one of the most important non-edible industrial oilseed crops cultivated in tropical and subtropical regions. It is widely recognized for its adaptability to diverse agro-climatic conditions, particularly in semi-arid and rainfed regions. Owing to its deep root system and drought tolerance, castor can thrive in marginal soils with comparatively lower water requirements than many other commercial crops. These characteristics make it an ideal crop for sustainable agriculture and climate-resilient farming systems.

India is the world's largest producer, processor and exporter of castor oil, contributing nearly 80–90% of global exports. Gujarat is the leading producer followed by Rajasthan, Andhra Pradesh, Telangana, Odisha and Karnataka. Growing global demand for renewable and eco-friendly products continues to strengthen India's position in the international market.

Castor oil has more than 700 industrial applications. It is extensively used in lubricants, hydraulic fluids, paints, varnishes, printing inks, cosmetics, pharmaceuticals, soaps, detergents, adhesives, sealants, polyurethane, nylon-11, engineering plastics, rubber products, leather chemicals, textile processing and biodegradable polymers. It is also used in aerospace and high-performance automotive industries because of its excellent lubrication properties.

The crop offers several advantages to farmers. It performs well under rainfed conditions, requires fewer inputs, provides stable returns, and can be cultivated on marginal lands. Castor fits well into crop rotations and contributes to livelihood security through employment in cultivation, processing and value addition.

After oil extraction, castor cake serves as a valuable organic manure rich in nitrogen, phosphorus and potassium. Although unsuitable as livestock feed

due to toxic compounds, it is widely used in organic farming for improving soil fertility.

Castor oil has long been used in Ayurveda and modern medicine. Pharmaceutical-grade castor oil is used as a stimulant laxative, while ricinoleic acid exhibits anti-inflammatory and wound-healing properties. Consequently, castor oil is incorporated into numerous cosmetic and personal care products.

The growing demand for bio-based chemicals, biodegradable plastics and sustainable industrial products is expected to increase the importance of castor in the coming decades. Research on improved hybrids, precision crop management and integrated pest management will further enhance productivity and profitability.

In conclusion, castor is a highly versatile industrial crop with immense economic, environmental and industrial significance. Its adaptability, renewable nature and expanding industrial applications make it one of the most promising oilseed crops for a sustainable future.

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