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CONTENT

ISSN: 3049-2289

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ISSN: 3049-2289

Waste to Wealth: Converting Kitchen Waste into Nutrients for Vegetable Crops

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Kitchen waste is an important component of household and municipal waste and is generated in large quantities every day. Improper disposal of these biodegradable materials can create environmental problems and contribute to greenhouse gas emissions. At the same time, kitchen residues contain considerable amounts of organic matter and plant nutrients that can be recovered and utilized in agriculture. Converting kitchen waste into compost, vermicompost or other organic amendments provides an opportunity to transform a disposal problem into a useful resource for vegetable production. Such recycling can improve soil organic matter, nutrient availability, moisture retention and overall soil health while reducing dependence on synthetic fertilizers. Composting also provides a practical method for reducing the environmental impacts associated with uncontrolled decomposition of organic waste. Therefore, the conversion of kitchen waste into nutrient-rich organic manure represents an effective approach for promoting sustainable vegetable cultivation, resource conservation and a circular agricultural system.

Introduction

The rapid growth of urban populations, changing food habits and increasing food consumption have resulted in a continuous increase in household and commercial kitchen waste. Food preparation and consumption generate large quantities of biodegradable materials such as vegetable and fruit residues, peels, leftover food, tea leaves, coffee grounds and eggshells. When these materials are discarded without proper treatment, they can increase the pressure on municipal waste-management systems and may cause environmental and sanitation problems. Food waste is not simply a disposal issue; it also represents a loss of valuable nutrients and resources. Organic residues contain carbon, nitrogen, phosphorus, potassium and other elements that can potentially be returned to the soil. Recycling these materials through appropriate biological processes can therefore convert waste into a useful agricultural input. Vegetable cultivation requires a continuous supply of nutrients and organic matter to maintain productive soils. Kitchen waste can contribute to this requirement when it is properly processed before application. Composting and vermicomposting are two important methods for converting biodegradable kitchen residues into stable, nutrient-rich organic amendments. Composting is a biological process in which microorganisms break down organic materials under controlled, oxygen-rich conditions. The final product is a relatively stable organic material that can be incorporated into soil. Vermicomposting uses earthworms along with microorganisms to transform organic residues into fine, nutrient-rich vermicompost. These approaches can help reduce waste accumulation while improving soil fertility. Thus, kitchen waste recycling provides a link between waste management and vegetable production. Instead of viewing organic kitchen residues as unwanted materials, they can be considered a source of nutrients for maintaining healthy soils and sustainable vegetable gardens.

ISSN: 3049-2289

What is Kitchen Waste?

Kitchen waste consists mainly of biodegradable materials generated during food preparation, cooking and consumption. Its composition varies according to household food habits, seasonal availability of produce, cultural practices and cooking methods.

Common components include:

- Vegetable and fruit peels
- Fruit and vegetable trimmings
- Leftover plant-based food
- Cereals and grains
- Tea leaves and coffee grounds
- Eggshells
- Small quantities of garden residues
- Other biodegradable food-preparation residues

The proportion of each material differs from one household or location to another. Plant-based residues generally form an important part of kitchen waste and can be particularly useful for composting.

Important Components of Kitchen Waste

Vegetable and Fruit Peels

Vegetable and fruit peels are among the most readily available kitchen residues. They contain organic matter, fibre and various minerals. Different types of peels have different nutrient compositions. Banana peels, for example, contain potassium and other minerals that are important for plant growth. Potato peels also contain useful nutrients and organic matter. Citrus and other fruit residues can contribute carbon and nutrients to composting mixtures. Rather than throwing these materials into general waste, they can be chopped into smaller pieces and added to a properly managed composting system. Smaller pieces generally decompose more rapidly because microorganisms can act on a larger surface area.

Tea Leaves and Coffee Grounds

Used tea leaves and coffee grounds are common household residues that can be incorporated into compost. They contribute organic material and some nutrients to the composting mixture. However, these materials should preferably be mixed with other organic residues instead of being applied excessively or as the sole fertilizer source. Combining different waste materials helps create a more balanced composting mixture.

Eggshells

Eggshells are primarily a source of calcium and can contribute mineral material to compost. They should be cleaned, dried and crushed before incorporation into compost so that they break down more effectively. Eggshells alone cannot supply all the nutrients required by vegetable crops. Their greatest value comes from combining them with other nutrient-rich organic materials.

Food Leftovers

Food leftovers may contain carbohydrates, proteins, minerals and other organic compounds. Plant-based leftovers can be valuable additions to compost. However, large amounts of meat, fish, dairy products, oily food and highly salted food should be handled carefully because they can produce unpleasant odours, attract pests and complicate compost management. For safe and efficient composting, kitchen waste should therefore be properly segregated before it is added to the composting unit.

Kitchen Waste as a Resource for Vegetable Production

The major advantage of recycling kitchen waste is that nutrients contained in organic residues can be returned to the soil. When converted into compost or vermicompost, kitchen waste can contribute organic matter and nutrients to vegetable-growing systems.

Regular addition of suitable organic amendments can:

- Improve soil structure
- Increase organic matter content
- Improve soil moisture-holding capacity
- Support beneficial soil microorganisms
- Enhance nutrient availability
- Improve root development
- Reduce organic waste accumulation
- Support sustainable vegetable production

The response of crops depends on the quality and maturity of the compost, soil characteristics, crop requirements and the quantity applied.

Composting of Kitchen Waste

Composting is one of the simplest and most practical methods of recycling biodegradable kitchen waste. It involves the biological decomposition of organic materials by microorganisms in the presence of oxygen.

Basic steps in kitchen-waste composting

1. Segregation: Separate biodegradable kitchen waste from plastic, glass, metal and other non-degradable materials.

2. Size reduction: Cut or chop larger vegetable and fruit residues into smaller pieces. This increases the surface area available to microorganisms and can accelerate decomposition.

3. Mixing: Combine moist, nitrogen-rich kitchen residues with relatively dry, carbon-rich materials such as dry leaves, straw, shredded paper or other suitable plant residues.

4. Moisture management: Maintain adequate moisture without making the compost excessively wet. Excess water can restrict aeration and create undesirable anaerobic conditions.

5. Aeration: Regular turning or mixing helps supply oxygen to the composting microorganisms.

6. Monitoring: Temperature, moisture, odour and the overall appearance of the material should be observed during decomposition.

7. Maturation: The compost should be allowed to mature until it becomes dark, crumbly and relatively uniform, with a pleasant earthy smell. Proper management of moisture, aeration, particle size and the carbon-to-nitrogen balance is essential for efficient composting.

Benefits of Kitchen-Waste Recycling in Vegetable Production

- Low-Cost Nutrient Source
- Improvement of Soil Health
- Nutrient Recycling
- Reduction in Waste
- Reduced Dependence on Synthetic Inputs
- Support for Sustainable Vegetable Production

Application in Vegetable Gardens

Mature compost or vermicompost can be incorporated into vegetable-growing soil before planting or used as an organic amendment during crop production according to crop and soil requirements. It can be particularly useful in soils with low organic matter. However, application rates should be based on compost quality, soil fertility status and crop requirements. Excessive application should be avoided because more organic amendment does not necessarily mean better crop growth. For safe vegetable production, compost should be mature, free from visible contaminants and produced through a properly managed process.

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A Win-Win for Farmers and the Planet: The Carbon Farming

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Carbon farming is a farm-based solution to climate change that provides revenue to farmers for shifting to soil carbon sequestration farming techniques. It is a process that involves monitoring, reporting, and verification to generate carbon credits and sold to organizations looking to offset their greenhouse gas emissions. By storing carbon in soil, farmers can earn additional income by carbon trading, reduce production costs, and build sustainable farming system, thus making carbon farming as a promising revenue stream for farmers. This article provides a comprehensive analysis of how carbon farming decreases atmospheric CO2 concentrations by increasing carbon stocks in soil. Carbon farming reduces global warming and improves agricultural sustainability through various techniques, including carbon sequestration, agroforestry, intercropping, cover crops, reduced fertilizer application, livestock management, reduced tillage, using organic mulch, working with biochar, etc. The article discusses the carbon farming initiatives and emission reduction projects and schemes, challenges such as farmer awareness, market instability etc. and future directions to enhance carbon farming in India.

Introduction

Carbon Farming refers to sustainable agricultural practices that aims to increase the storage of carbon in biomass/ trees and soil while reducing greenhouse gas emissions. Carbon farming aims at maximizing carbon sequestration through: (a) Geological sequestration i.e. storing anthropogenic CO2 deep underground in geological formations to prevent it from entering the atmosphere, (b) Oceanic sequestration i.e. storing carbon in the oceans either through biological pump that involves marine organisms, phytoplankton absorb CO2 during photosynthesis and after their death, they sink taking carbon to deeper ocean layers or through physical pump that involves CO2 dissolved in cold deeper ocean water and is transported by ocean currents. (c) Terrestrial sequestration i.e. storing carbon in forests, soils, and vegetation. It mainly occurs through photosynthesis, whereby plants absorb CO2 and convert it into organic carbon compounds. Carbon farming is also known as “Regenerative Agriculture” because it restores soil health and fertility by increasing soil organic matter, reverses environment degradation, mitigates climate change and enhances ecosystem services. Carbon farming provides economic incentives to farmers through carbon trading. Carbon can be traded in the form of credits (1 carbon credit = 1 Metric ton of CO2 equivalents). The act of buying and selling of carbon credits is called carbon trading or Cap and Trade system (CAT).

Techniques for Carbon Farming:

Agroforestry: The integration of trees with agriculture is called Agroforestry. It contributes climate change mitigation through carbon sequestration and is an important component of carbon farming. Agroforestry sequesters carbon by storing carbon in above ground (trees, shrubs, and crops) and below ground biomass (roots and soil organic matter). Trees within agroforestry systems uptake atmospheric CO2 during photosynthesis and store it in their leaves, branches, and trunks. Tree leaves, twigs and organic residues fall to the ground and enrich the soil organic content. As they break

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down over time, they release carbon into the ground, which goes towards long-term carbon storage. Agroforestry also provides an additional source of income to farmers.

Cover Crops: Cover crops play a vital role in carbon farming by acting as a link between atmospheric CO_2 and long-term soil carbon storage. When these crops are grown between main crop cycles, they capture CO_2 through photosynthesis and store it in their roots, stems, and leaves. When incorporated into soil, organic matter increases and fertility is enhanced. Deep-rooted species are particularly effective as they deposit carbon deeper into the soil making it less prone to decomposition. Moreover, cover crops protect existing soil carbon by forming a protective layer that protects the soil from erosion.

- **Zero-Tillage**: Frequent and heavy tilling increases the rate of CO_2 release from the soil and breaks up soil structure which reduces the productivity of the soil. Zero tillage eliminates ploughing operations, reducing CO_2 emissions from machinery. Moreover, soil aggregates remain stable and trap organic carbon within, physically protecting it from microbial attack.
- **Biochar application:** Biochar is produced through pyrolysis. During this process, a large portion of the carbon in the biomass is converted into stable aromatic carbon rings. Unlike the crop residues or manure that decompose quickly and release CO_2, biochar is highly resistant to microbial breakdown. It can remain in soil for hundreds and thousands of years, effectively locking carbon in soil.
- **Terra-Preta:** Terra Preta (meaning "black earth" in Portuguese) is an ancient biochar-based soil management technique. It is made by adding charcoal (biochar), food waste, manure, bones and organic residues into nutrient-poor tropical soil. The charcoal (biochar) in Terra Preta is highly stable and locks carbon in soil for centuries.
- **Rotational grazing:** It involves periodically relocating livestock to new pastures, this practice prevents overgrazing and allows previously grazed land to rejuvenate and grow deeper root systems. These roots deposit soil organic matter which increases soil organic carbon over time. This practice prevents soil erosion, increases water retention and overall ecosystem resilience, making it a key strategy in regenerative agriculture.
- **Reduced fertilizer application:** Chemical fertilizers reduce the capacity of soil to sequester carbon and significantly cuts greenhouse gas emissions which are released during the manufacturing of fertilizers. Organic manures and cover crops are used for nutrient management in place of these fertilizers which reduces the cost of cultivation and makes farming sustainable and profitable.
- **Integrating Silvi-pastoral systems:** Integrating trees with livestock increases carbon stocks both above and below ground. It provides shade and fodder for animals besides maintaining soil health and climate resilience.

Significance of Carbon Farming:

- **Climate Change Mitigation:** Carbon farming is one of the powerful weapons to fight climate change by reducing Greenhouse gas emission by sequestering atmospheric CO_2 in soil and biomass turning agriculture farms from emitters to sink of carbon. Key practices such as agroforestry, conservation tillage, biochar application and improved crop and livestock management help in achieving this.
- **Soil Health Enhancement:** Carbon Farming boosts soil health by increasing soil organic matter and water retention capacity of soil. In addition to this it also reduces soil erosion resulting in amplified crop yields and agricultural productivity.
- **Biodiversity Enrichment:** Carbon farming enhances biodiversity by safeguarding beneficial microbes in soil, attracting beneficial insects and

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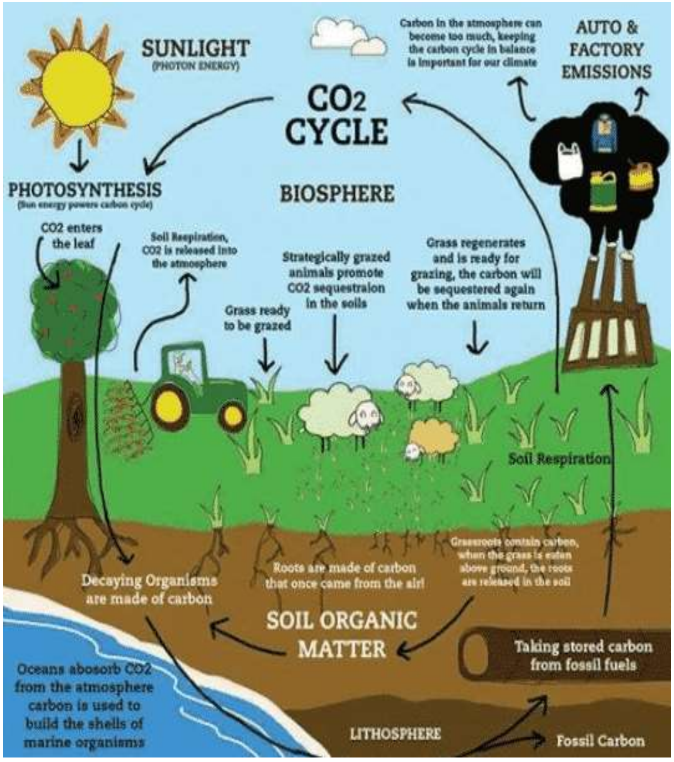
pollinators that enhances crop health and reduces dependency on pesticides.

- **Economic opportunities:** Carbon farming practices offers significant economic opportunities by allowing farmers to earn income from carbon credits and reduces input costs (fertilizers, diesel). The emerging carbon economy creates jobs in data tracking, verification, and project development. India's carbon stock has reached 30.43 billion tons of CO2 equivalent, indicating that the country has already achieved 2.29 billion tons of additional carbon sequestration compared to the 2005 baseline, approaching its target ofN 2.5 to 3 billion tons by 2030.



Policies and Institutional support:

➢ National action plan on climate change: NAPCC was released by the Prime Minister on June 30, 2008 focusses on national strategy to enable country to adapt to climate change and enhance ecological sustainability through sustainable development. There are 8 national missions under NAPCC which encompasses The National Mission for a Green India and National Mission on Sustainable Agriculture and Carbon farming directly supports these missions under NAPCC by promoting carbon sequestration, climatesmart agriculture and sustainable land management.

➢ National Mission on Sustainable Agriculture: The National Mission on Sustainable Agriculture (2014-15) is a key component of the National Action Plan on Climate Change (NAPCC) which considers the sustainable use of land and resources under agriculture. It promotes subsidies and financial help to encourage the adoption of climate-resilient technologies, efficient use or water resources, conservational tillage techniques, all of which contribute towards carbon farming.

➢ Soil Health Card Scheme: This scheme launched by the GOI on 19 Feb, 2015, guides farmers on soil improvement by providing them with a printed report on their soil's nutrient status (12 parameters like NPK, micronutrients, pH etc.) improving soil fertility and productivity which enhances soil's capacity for carbon sequestration, a core aspect of carbon farming.

➢ National Agroforestry policy and sub-mission on agroforestry (SMAF): India was the first country in the world to adopt agroforestry policy on 2014. Its main agenda is to integrate trees with crops and livestock which increases productivity, income, and environmental resilience. SMAF was launched in 2016 onwards.

under National Mission for Sustainable Agriculture (NMSA). Its main objective is to promote farmers to adopt agroforestry by providing financial assistance for nursery, sapling distribution, and plantation.

➢ Carbon Credit Trading Scheme: The Carbon Credit Trading Scheme, 2023 introduced under the Energy Conservation (Amendment) Act, 2022, replaces the Perform, Achieve, and Trade (PAT) scheme to establish the Indian Carbon Market (ICM), aligning with India's climate commitments under the Paris Agreement. The CCTS is a market-based mechanism to decarbonize the Indian economy by pricing greenhouse and facilitates carbon trading. It issues Carbon Credit Certificates (CCC) each representing 1 ton CO2 equivalent reduction.

Challenges in the adoption of Carbon farming: Despite its potential for climate change mitigation and sustainable agriculture, the adoption of carbon farming is hindered by multiple challenges. One of the major barriers is economic uncertainty associated with carbon farming practices. Farmers face high initial costs for adopting practices such as cover cropping, agroforestry, etc., while financial returns from carbon credits are delayed and uncertain. Lack of knowledge, training and awareness about the mechanism and benefits of carbon farming further limits its adoption. A 2022 survey by the National Bank for Agriculture and Rural Development (NABARD) revealed that most of Indian farmers were unaware of carbon farming opportunities. Additionally, limited technical expertise on measurement, reporting and verification (MRV) of soil carbon is a significant challenge. It is very difficult to accurately measure soil carbon changes over time. High cost of monitoring and verification particularly for small landholders limits this practice. Limited access to carbon markets, especially in developing countries and insufficient digital and institutional infrastructure for participation in carbon trading poses threat in the extension of carbon farming techniques.

Future Directions to Enhance Carbon Farming:

➢ Scalable MRV System: Applying knowledge of artificial intelligence (AI), machine learning (ML), satellite imagery, and remote sensing to develop cost-effective, transparent, and credible MRV system which is essential for wider adoption across various farm sizes.

➢ Policy support and incentives: Establishing farmer-friendly policies like simplified certification processes, subsidies for initial investments and assured minimum carbon credits prices to mitigate market fluctuation. Integration of carbon farming into national climate action plans and agricultural policies.

➢ Precision Agriculture: Use of IoT devices and drones for hyper-customized advisories for irrigation, nutrient management, and yield optimization. This helps farmers adapt to new practices and minimizes the overall environmental footprint of farming operations.

➢ Capacity building & farmer awareness: Encouraging training programs, demonstrations and extension services for farmers helps in wider adaptability of carbon farming practices. Carbon farming concepts are to be integrated in agricultural education and curricula.

Research & Innovation: Enhancing research practices to develop low-cost, high impact carbon farming practices. Development of improved crop varieties with deeper root systems and higher biomass can increase carbon inputs in soil.

Conclusion: Carbon Farming provides a crucial way to achieve the goal of climate change mitigation through on-site carbon sequestration and reduction of greenhouse gas emission. It also considers its role in sustainable agriculture development, food security, and supply of multiple ecosystem services. Additionally, the potential for monetization through carbon credits provides economic incentives for farmers, especially for rural communities, making carbon farming both environmentally and economically viable. Techniques like agroforestry, cover cropping, management of livestock, crop residues and biochar application enhances soil organic carbon, improves soil structure and biodiversity. Therefore, promoting carbon farming through supportive policies, awareness programs and scientific innovation is essential for achieving the global target of sustainable development.

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The Genetic Treasure Hidden Inside Wild Plants

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Walk along the bunds of a paddy field, the edge of a wheat plot, or an unploughed patch near a tomato nursery, and you may brush past a scraggly, unremarkable-looking weed without a second glance. Yet that very weed could be a wild relative of the crop growing right beside it and it may be quietly carrying a gene that no amount of fertiliser, irrigation, or pesticide can give a modern variety: the ability to survive a flood, shrug off a disease, or grow in soil too salty for its cultivated cousin. Crop wild relatives (CWR) the undomesticated ancestors and close cousins of the plants we eat are increasingly recognised as one of agriculture's most valuable, and most overlooked, genetic treasuries.

What Exactly Are "Crop Wild Relatives"?

Every cultivated crop, from rice to tomato, descended from a wild ancestor that once grew freely in forests, marshes, or grasslands. Crop wild relatives are these wild ancestors and their close botanical cousins that can still interbreed, or be crossed with some scientific assistance, with the crops we farm today. *Oryza rufipogon*, for instance, is the wild rice from which our cultivated *Oryza sativa* was domesticated thousands of years ago, while *Solanum pimpinellifolium*, a small red-fruited weed of South America, is the wild progenitor of the tomatoes on our plates today (Wang *et al*., 2020). Unlike our modern varieties, which have been bred for centuries to maximise yield, uniformity, and taste under carefully managed farm conditions, wild relatives were never pampered. They fought for survival on their own, in flood-prone deltas, drought-hit plains, and disease-ridden thickets. In doing so, they held on to a far broader set of genes for coping with stress than what remains in our modern, "improved" crops (Kapazoglou *et al*., 2023).

Why Modern Crops Need Their Wild Cousins

Modern plant breeding has been remarkably successful at raising yields, but that very success has come at a cost: a shrinking gene pool. Each time breeders selected the highest-yielding, best-looking, or most uniform plants over generations, they inevitably left many other genes behind including many that conferred resistance to pests, diseases, and harsh climates. As cultivars become more genetically similar to one another, they also become more inadequate in genes needed to withstand biotic stresses such as diseases and pests, and abiotic stresses such as drought, cold, and salinity (Benlioğlu & Adak, 2019).

This is where crop wild relatives step in. Because they were never subjected to the narrow selection pressures of domestication, they retain far greater genetic and phenotypic variability, giving breeders a rich, largely untapped gene pool. In an era of erratic rainfall, rising temperatures, and expanding salt-affected soils, this reservoir of "wild toughness" is exactly what breeders need to broaden the genetic base of our cultivated varieties and meet the twin challenges of food security and climate change (Kapazoglou *et al*., 2023).

Treasure Hunts That Paid Off: Real Success Stories

Rice that can tolerate salt: Rice is the most salt-sensitive of all cereal crops, yet its wild ancestor *Oryza rufipogon* has been found to tolerate salinity far better than cultivated rice. Researchers have mapped genetic regions (quantitative trait loci, or QTLs) from wild rice that are linked to salt tolerance at the seedling stage, offering breeders new genetic resources to develop salt-tolerant rice varieties for the salt-affected coastal and delta soils that are expanding worldwide (Wang *et al*., 2017).

Wheat that resists rust: Rust diseases are among the biggest threats to wheat production globally, and breeders have long turned to wild goatgrass species of the genus *Aegilops* for resistance genes. Scientists successfully introgressed or transferred, a new leaf rust resistance gene from the wild wheat relative *Aegilops peregrina* into cultivated bread wheat, and pinpointed its exact location on the wheat chromosome using modern molecular mapping tools a gene now available for deployment in future rust-resistant wheat varieties (Narang *et al*., 2020).

Tastier, tougher tomatoes: The small, wild, red-fruited *Solanum pimpinellifolium*, found growing along the Andes, has become an important genetic donor for modern tomato breeding because of its remarkable stress tolerance and intense flavour. Comparing its full genome sequence with that of a modern cultivated tomato has revealed thousands of genetic differences linked to traits such as fruit weight and the lycopene content that gives tomatoes their red colour and antioxidant value, opening new routes to breed tomatoes that are both more nutritious and more resilient (Wang *et al*., 2020).

India's Vaults of Genetic Treasure

India is fortunate to sit within the “Hindustani Centre of Origin,” one of the world's recognised centres of crop diversity, home to the wild relatives of rice, sugarcane, green gram, and many other crops important to our food security. Recognising the value of this natural inheritance, the ICAR-National Bureau of Plant Genetic Resources (NBPGR), New Delhi, serves as the country's nodal agency for collecting, characterising, and conserving plant genetic resources, including crop wild relatives, and now maintains more than 4.68 lakh (468,000) accessions in its National Genebank, one of the largest such collections in the world (ICAR-NBPGR). This national effort forms part of a larger, worldwide movement. Governments have recently reaffirmed their commitment to strengthening such genebanks: in India, plans announced in 2025 for an expanded national Gene Bank aim to safeguard the country's genetic resources and food security for future generations (IMPRI Impact and Policy Research Institute, 2025). Every accession of a wild rice, wild pulse, or wild vegetable relative conserved in cold storage today is, in effect, a safety deposit for tomorrow's plant breeders.

The Race Against Time: Challenges in Using Wild Relatives

Turning this wild genetic treasure into farmer-ready varieties is not always straightforward. Wild relatives often carry the desired gene bundled tightly with many undesirable ones a problem breeders call “linkage drag” making it difficult to transfer only the useful trait without also dragging along poor yield, unwanted growth habits, or bitter taste. Differences in chromosome number between wild and cultivated species can also make the two incompatible for crossing, and some wild species remain poorly studied or barely represented in genebank collections at all (Benlioğlu & Adak, 2019). Perhaps the most urgent problem is time itself. Habitat loss, climate change, and unchecked land-use change are pushing many crop wild relatives towards extinction even before scientists have had the chance to study them, let alone use them in breeding. Modern tools such as marker-assisted selection, genomic sequencing, and tissue culture-based cryopreservation are helping to overcome some of these old barriers, but conservation must keep pace with, or stay ahead of, this quiet loss of wild diversity.

Conclusion: Guarding the Treasure for Tomorrow

The next time you see an unassuming wild grass by a rice field or a weedy nightshade near a vegetable plot, remember that it may hold the very trait that saves a future harvest from a drought, a flood, or a new strain of disease. Crop wild relatives are, quite literally, nature's insurance policy for agriculture; a genetic treasure built over millions of years of evolution that no laboratory can recreate from scratch. For farmers, students, and scientists alike, the lesson is the same: conserving these wild plants in their natural habitats and in genebanks is not a luxury for botanists, it is a direct investment in the food security of generations to come. As breeders continue to unlock and deploy these hidden genes through classical breeding and modern biotechnology, the humble, wild cousins of our crops may well prove to be among agriculture's most important allies in the fight against a changing climate.

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Kattuyanam and Mappillai Samba: The New Raw Material for Modern Rice Breeding

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In a cold-storage gene bank in Coimbatore named after the legendary rice breeder Dr. K. Ramiah, more than 4,300 rice accessions sit quietly in packets, including 136 traditional landraces collected from across Tamil Nadu (Amudha *et al.*, 2023). Most farmers today have never grown them; most consumers have never eaten them. Yet two of these old, unglamorous varieties; Kattuyanam and Mappillai Samba are quietly becoming some of the most sought-after genetic material in Indian rice breeding programmes. Neither was bred for the high-input, high-yield world of modern agriculture. Both were shaped, over centuries, by farmers simply saving and resowing the seed that survived in their own fields and served their own kitchens. That accidental selection turns out to have packed both varieties with exactly the traits today's breeders are chasing: resilience, nutrition and genetic diversity.

Two Landraces, Two Legends

Long before molecular markers existed, Tamil farming communities had their own way of encoding a variety's traits in its name. Kattuyanam is said to grow so tall and dense that a wild elephant (kattu yaanai) could hide inside a field of it; in practice, this reflects a genuinely tall, vigorous plant architecture, with recorded heights of 138–170 cm compared with 90–110 cm for most modern semi-dwarf varieties (Ashokkumar *et al.*, 2020). That height turns out to be functional rather than decorative: a pureline selection from Kattuyanam, released as the variety TNR 2, was specifically valued for its tolerance to deep-water conditions, letting the plant keep its head above rising floodwater in low-lying fields (Amudha *et al.*, 2023). Mappillai Samba, meaning "bridegroom's rice" in Tamil, carries an entirely different story. In parts of rural Tamil Nadu, a prospective groom was traditionally given a thick kanji (porridge) made from this bold, red-husked rice before a test of strength; often lifting a heavy stone to prove his readiness for marriage (Amudha *et al.*, 2023). The folklore turns out to have a biochemical basis: Mappillai Samba's red pericarp is rich in anthocyanins and phenolic compounds, and the grain is unusually dense in iron and other micronutrients compared with polished white rice (Rajagopalan *et al.*, 2022).

The Nutrition Hiding in Plain Sight

When researchers at Tamil Nadu Agricultural University ran a non-targeted metabolomic analysis comparing Mappillai Samba against a modern white rice line, they detected 113 distinct metabolites across 21 chemical classes in the grain, including therapeutically relevant phenylpropanoids, phytosterols, flavonoids and polyamines (Rajagopalan *et al.*, 2022). Three metabolic pathways; phenylpropanoid biosynthesis, steroid biosynthesis, and ubiquinone and terpenoid-quinone biosynthesis accounted for most of the difference between the two grain types, giving breeders a specific biochemical map to work from rather than a vague sense that "red rice is healthier" (Rajagopalan *et al.*, 2022). Kattuyanam, too, turns out to be nutritionally dense rather than simply tall. Direct mineral analysis found it carrying 437 mg of phosphorus and over 154 mg of magnesium per 100 g among the highest values recorded across a panel of Tamil Nadu landraces alongside respectable iron and zinc content (Amudha *et al.*, 2023). None of this was engineered; it is simply what centuries of farmers, saving seed from the plants that served their households best, ended up preserving.

Built to Survive: Drought and Deep Water

Modern breeding increasingly needs donor parents that can shrug off water stress in either direction too little or too much and both landraces qualify. In a recent screening of rice landraces for drought tolerance using a molecular marker linked to a known drought-responsive gene, Kattuyanam was among the landraces found to carry the favourable, resistant allele, alongside Garudan Samba, Keerai Samba, Kannan Samba and Manag Kuruvai (Ranjith *et al.*, 2025). The study's authors specifically flagged these landraces as candidate donor parents for future drought-tolerance breeding programmes (Ranjith *et al.*, 2025). At the opposite extreme, Kattuyanam's height and vigorous growth habit made it valuable enough to be formally released as TNR 2, a variety selected specifically for its ability to tolerate deep-standing water a trait of growing importance as erratic monsoon rainfall brings both drought and flash flooding to the same rice-growing regions within a single season (Amudha *et al.*, 2023). Breeders rarely find both drought tolerance and flood tolerance bundled conveniently in one modern high-yielding variety; landraces like Kattuyanam are often where that kind of dual resilience still survives.

From Field Curiosities to Breeding Material

Tamil Nadu has a long history of turning landraces into working breeding stock rather than leaving them as museum pieces. GEB 24 and TKM 6, two earlier landrace-derived selections, went on to become foundational parents used in breeding programmes not just in India but at IRRI in the Philippines, and in Sri Lanka and Thailand, prized respectively for grain quality and multiple disease resistance (Amudha *et al.*, 2023). Kattuyanam and Mappillai Samba are now being evaluated for a similar journey not to replace modern high-yielding varieties, but to supply the specific genes those varieties lack: deep-water tolerance, a validated drought-resistant allele, and a biochemically mapped pathway to red, iron-rich, high-antioxidant grain. A landscape-level assessment of traditional rice diversity in the Cauvery Delta, a region especially exposed to drought, flooding and shifting pest pressure, formally identified Kattuyanam among twenty priority traditional varieties recommended for active use in climate-resilient breeding strategies for the zone (Muralikrishnan *et al.*, 2021). That is a significant shift in status: from a landrace grown quietly in small pockets by a handful of farmers, to a named genetic resource in a regional climate-adaptation breeding plan.

Why “Raw Material” Matters for the Future of Rice

Modern rice breeding faces a quiet but serious problem: decades of selecting elite varieties from a relatively narrow set of parental lines has thinned out the genetic diversity available to breeders, exactly as new pressures from climate change, emerging pest biotypes and nutritional deficiencies demand more of it. Landraces such as Kattuyanam and Mappillai Samba represent genetic diversity that mainstream breeding largely bypassed during the Green Revolution, when the priority was maximising yield under assured irrigation and fertiliser (Amudha *et al.*, 2023). That diversity did not disappear, it simply kept being grown, in small quantities, by farmers who valued it for reasons breeders were not yet measuring: taste, ritual significance, resilience in a bad year, or a grandmother's conviction that red rice was good for you. Today, with genetic markers and metabolomic profiling able to pinpoint exactly which traits are worth chasing and which genes carry them, that same old seed is being read in an entirely new way. The gene bank packet and the field of Kattuyanam growing tall enough to hide an elephant are, in the end, the same genetic resource one simply waiting for the tools to properly understand it.

Conclusion

Kattuyanam and Mappillai Samba were never bred in a laboratory; they were bred, unknowingly, by generations of Tamil farmers selecting for taste, ritual value and survival in difficult seasons. What modern genetics is now doing is not replacing that process but reading its results identifying the specific alleles behind Kattuyanam's flood tolerance and drought resilience, and the specific metabolic pathways behind Mappillai Samba's iron-rich, antioxidant grain. As breeders look for new raw material to build climate-resilient, nutritionally richer rice varieties, these two landraces are a reminder that some of the most valuable genetics in modern crop science were never lost they were simply waiting, quietly, in a farmer's field, for someone to ask the right question.

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Traditional Rice Defeating Climate Change: The New Path Shown by Genetic Science

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Until as recently as 1970, India was home to more than 100,000 distinct varieties of rice, each one patiently selected and re-selected by generations of farmers to suit a particular soil, climate, and taste. Then came the Green Revolution: a small number of high-yielding, genetically uniform varieties spread rapidly across the country, and thousands of these local landraces traditional, farmer-developed varieties quietly disappeared from the fields where they had grown for centuries. Today, as erratic rainfall, flash floods, and creeping soil salinity threaten rice harvests across Asia, scientists are turning back to the very landraces that were once set aside, discovering that these old, unglamorous plants carry genetic solutions modern breeding cannot easily invent from scratch.

What Makes a Landrace Special?

A landrace is not a wild plant; it is a cultivated variety shaped jointly by nature and by generations of farmers who saved seed from the plants that survived best in their own fields, year after year. Because this selection happened locally and without the uniformity demanded by modern commercial farming, landraces evolved to cope with the particular stresses of their home region, whether that meant tolerating salt water, surviving underwater during monsoon floods, or growing in nutrient-poor soil. This long, decentralised process has left landraces with substantially greater genetic diversity than the modern high-yielding varieties that replaced them, which is precisely why breeders now regard them as an essential resource for developing durable, climate-resilient rice (Sahu *et al*., 2017). This is not a phenomenon unique to India. Around the world, traditional rice landraces adapted to specific agro-ecological niches are increasingly recognised as irreplaceable repositories of adaptive genes for drought, salinity, poor soils, and temperature extremes exactly the pressures that a changing climate is intensifying (Kou *et al*., 2026).

Pokkali: The Salt-Defying Rice of Kerala

Along the brackish, tide-affected paddies of coastal Kerala, farmers have grown a tall, hardy rice landrace called Pokkali for generations, prized for its ability to survive in fields where seawater regularly mixes with fresh water. Pokkali itself is not a high-yielding or particularly grain-attractive variety, but scientists discovered that it harbours a powerful cluster of genes on chromosome 1, named *Saltol*, that helps rice seedlings manage the balance of sodium and potassium inside their cells the key physiological trick that allows a plant to keep functioning when its roots are bathed in salt (Thomson *et al*., 2010). Breeders have since introgressed, or precisely transferred, the *Saltol* region out of Pokkali and into a more refined, less photoperiod-sensitive breeding line, and from there into popular high-yielding rice varieties, using DNA markers to track the exact segment of Pokkali's chromosome being moved. As a result, farmers in coastal and salt-affected regions of South and Southeast Asia now have access to rice varieties that combine the grain quality and yield of modern rice with the salt tolerance once found only in a low-yielding landrace that could never have supported large-scale commercial cultivation on its own.

FR13A: The Rice That Survives Underwater

Along India's flood-prone river plains, another landrace once known mainly to local farmers proved just as remarkable in a different way. FR13A, an Indian flood-tolerant rice line derived from the landrace Dhalputtia, can remain fully submerged under floodwater for two weeks or more and still resume growth afterward, whereas most rice varieties die within about a week underwater. Scientists traced this ability to a genetic region on chromosome 9 that they named *SUB1*, and eventually identified the single gene within it, SUB1A, as the key genetic switch responsible for this remarkable survival trait (Xu *et al*., 2006). Rather than desperately trying to keep growing underwater and exhausting its energy reserves, a rice plant carrying *SUB1A* essentially goes dormant, conserving its resources until the floodwater recedes, then resumes normal growth. Using marker-assisted breeding, scientists transferred this single gene from *FR13A* into several widely grown, high-yielding rice varieties without disturbing their other desirable traits, producing submergence-tolerant “mega-varieties” that are now grown across flood-prone areas of South and Southeast Asia a direct, practical legacy of a landrace that farmers had quietly relied on for generations before science ever explained why it worked.

Guarding a Living Library

Stories like Pokkali and FR13A are only useful because someone kept the seed alive long enough for science to study it. In Chhattisgarh, often called the “rice bowl of India,” researchers cataloguing more than 23,000 recorded rice germplasm lines have used DNA-based fingerprinting to map the genetic relationships among hundreds of local landraces, work that is essential for identifying which traditional varieties carry unique, useful genetic material before that material is lost (Sahu *et al*., 2017). Similar documentation efforts are underway across India's rice-growing regions, including the culturally rich and highly diverse landraces of the north-eastern Himalayan states. This conservation work matters because genetic erosion, the quiet disappearance of landraces as farmers shift to a handful of commercial varieties, is a global pattern, not just an Indian one. In China's Yunnan Province, for instance, conservationists have combined on-farm cultivation, seed-bank storage, community engagement, and modern genomic characterisation to safeguard a single high-altitude landrace called Pantiange Heigu, treating it as a model for how traditional rice diversity can be kept both genetically intact and economically viable for the farming communities who still grow it (Kou *et al*., 2026).

A Two-Way Relationship Between Old and New

It would be a mistake to see this as old rice simply being replaced by new rice, or vice versa. What is actually happening is a two-way relationship: modern genomic tools such as DNA markers and marker-assisted breeding are what make it practical to extract a single useful gene, such as *Saltol* or *SUB1A*, out of an otherwise low-yielding landrace without also inheriting all of its undesirable traits, such as tall, lodging-prone stems or poor grain quality. In turn, traditional landraces are what supply the raw genetic material that modern breeding could never have invented on its own, because it took hundreds of years of real-world selection, under real floods and real salt water, to produce it. This partnership between farmer wisdom and genetic science is likely to matter even more as climate change makes floods, droughts, and salinity events more frequent and severe. Every landrace lost to genetic erosion before it can be studied represents a potential climate-resilience gene lost along with it which is why documenting, conserving, and screening India's remaining traditional rice diversity is not simply an act of heritage preservation, but an active strategy for future food security.

Conclusion

The rice that once grew quietly in a farmer's flood-prone field or salt-affected paddy, overlooked for its low yield and unfashionable grain, is turning out to hold some of the very genes modern agriculture now urgently needs. Pokkali and FR13A are only two of the more famous examples; thousands of other traditional rice landraces across India and the world almost certainly hold genetic secrets of their own, still waiting to be studied. As climate change intensifies the pressures on rice farming, the path forward may depend as much on looking back into the deep genetic memory bred into traditional rice by generations of farmers as it does on any new laboratory technology.

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Plants Defying Pests: Chemical-Free Natural Protection

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For most of the last century, protecting a crop from a hungry insect has meant reaching for a sprayer. That approach is fraying at the edges. Insects evolve resistance to insecticides faster than new chemicals can be developed, residues raise consumer and environmental concerns, and beneficial species such as pollinators and natural predators are often collateral damage from broad-spectrum sprays (Kumaraswamy & Huang, 2026). Quietly, though plants have been running their own pest-control programme for hundreds of millions of years one built entirely out of genes, chemistry and ecology, with no spray can required. Understanding how plants defend themselves without our help is opening a genuinely chemical-free path to crop protection, one that breeders are now learning to put to deliberate use.

A Plant's Own Immune System

Plant resistance to pests is not a single trick but a layered system. Constitutive defences are always switched on tough leaf cuticles, waxy surfaces, and trichomes (tiny hair-like outgrowths) that physically snag or poison small insects before they can settle down to feed (Kumaraswamy & Huang, 2026). Induced defences, by contrast, activate only after an attack begins, triggered by the plant's ability to sense insect saliva, egg-laying secretions, or wound signals and respond within hours through hormone pathways built around jasmonic acid, salicylic acid and ethylene (Kumaraswamy & Huang, 2026). Breeders describe the outcomes of these defences using three classic terms: antixenosis, where the plant simply becomes unattractive for feeding or egg-laying; antibiosis, where compounds inside the plant directly harm the pest's growth, survival or fertility after it feeds; and tolerance, where the plant shrugs off damage and keeps yielding regardless (Kumaraswamy & Huang, 2026). Underneath all three sits a genetic layer of resistance (R) genes, which recognise specific molecular signatures from an attacking insect or pathogen and switch on a rapid, targeted immune response the plant equivalent of a security system that recognises a specific intruder's face.

Chemical Weapons, Grown Not Sprayed

Inside their tissues, plants manufacture an extraordinary chemical arsenal known as secondary metabolites; compounds not needed for basic growth but produced specifically for defence. Terpenoids, alkaloids, phenolics, flavonoids and glucosinolates act as toxins, feeding deterrents or digestive enzyme inhibitors, and their concentrations often spike sharply the moment a herbivore starts feeding (Kumaraswamy & Huang, 2026). A chilli plant under attack, for instance, ramps up both jasmonic acid and salicylic acid signalling almost immediately, while an eggplant deploys salicylic-acid-driven systemic acquired resistance to brace tissue far from the original bite (Kumaraswamy & Huang, 2026). These are not blunt instruments. Glucosinolates in mustard-family crops specifically deter weevils; protease inhibitors and lectins interfere with an insect's ability to digest protein at all; and some compounds work indirectly, priming neighbouring, undamaged parts of the same plant or even nearby plants to mount a faster defence if the attack spreads (Kumaraswamy & Huang, 2026). It is in effect, an early-warning network running entirely on plant chemistry.

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Calling for Backup: Volatiles and the Push–Pull Strategy

Some of the cleverest plant defences do not attack the pest directly at all, they call in reinforcements. When herbivores feed, many plants release a distinctive blend of airborne chemicals called herbivore-induced plant volatiles (HIPVs), which drift through the air and attract the natural enemies of the very insect doing the damage parasitic wasps, predatory bugs, and other biological control agents (Munawar *et al*., 2023). This principle underlies one of Africa's best-known sustainable pest-control successes: the "push–pull" cropping system. Maize is intercropped with a repellent forage legume such as Desmodium (the "push") and bordered with an attractive grass such as Napier grass (the "pull"), a combination reported to reduce fall armyworm damage by more than 80% in field trials while also boosting fodder yields (Sobhy *et al*., 2022). Interestingly, the underlying mechanism has recently proven more subtle than first thought: rather than repelling egg-laying moths through strong volatile emissions as originally proposed, current evidence suggests Desmodium may work chiefly by physically snagging and starving young caterpillars that try to disperse through its dense, hairy foliage, a reminder that even a well-established green technology keeps yielding new science as it is studied more closely (Erdei *et al*., 2024). On a smaller scale, home and market gardeners get a similar effect from companion planting: basil and French marigold interplanted with pepper release eugenol and other volatiles that measurably repel aphids from the main crop (Munawar *et al*., 2023).

Breeding Resistance In: Genes That Say No to Pests

Where a wild relative of a crop has evolved strong natural resistance, breeders can move that trait into modern, high-yielding varieties without spraying a single chemical. Rice offers the best-documented example. Nearly 40 resistance genes against the brown planthopper, one of Asia's most destructive rice pests, have been identified in cultivated rice and its wild relatives, including *Oryza rufipogon*, *O. officinalis* and *O. nivara* (Kumaraswamy & Huang, 2026). One of these, Bph6 was found to encode a protein located at the cell's exocyst a structure involved in transporting material to the cell surface and confers broad resistance across multiple planthopper populations when bred into elite cultivars (Guo *et al*., 2018). Using marker-assisted selection, breeders can now track these resistance genes through generations of crosses with DNA markers alone, without needing to expose every plant to live pests to see which ones survive. This has allowed genes such as *Bph31*, originally found in a resistant rice line, to be introgressed into a widely grown variety, strengthening its defences while keeping its familiar yield and grain quality intact (Kumaraswamy & Huang, 2026). Because a single resistance gene can eventually be overcome as pest populations adapt, breeders increasingly stack several different resistance genes together in one variety a strategy called gene pyramiding to make the protection harder for pests to evolve around.

The Next Generation: RNA Sprays and Precision Tools

The newest chemical-free tool in the pipeline is not really a chemical at all: RNA interference (RNAi). This technique uses double-stranded RNA matched to a specific gene inside a target pest; once an insect ingests it, its own cellular machinery silences that gene, disrupting a process essential for survival, and closely related, non-target species are left untouched because the RNA sequence is so specific (Chen *et al*., 2025). In late 2023, U.S. regulators approved the first sprayable RNA-based biopesticide, aimed at the Colorado potato beetle, marking a significant step toward commercial, non-transgenic RNAi products that farmers could apply much like a conventional spray, but without leaving toxic residues behind (Chen *et al*., 2025). Alongside RNAi, gene-editing tools such as CRISPR/Cas9 are being used to sharpen a plant's existing defences; for example, by fine-tuning the genes that control volatile release or trichome density rather than introducing anything foreign at all (Kumaraswamy & Huang, 2026). Combined with faster genome scanning and marker-assisted breeding, these tools mean that "chemical-free" protection is no longer a niche or old-fashioned idea; it is becoming one of the most technologically advanced areas of crop science.

Conclusion: Working With the Plant, Not Against the Pest

None of this means chemical pesticides will disappear overnight, and none of these strategies works in isolation forever; pests adapt, and durable protection usually comes from combining several defences at once. But the direction of travel is clear. Whether it is a trichome that snags a caterpillar, a burst of jasmonic acid that poisons a beetle's gut, a wasp summoned by an airborne distress signal, or a resistance gene quietly inherited from a wild ancestor, plants already possess a remarkably sophisticated toolkit for defending themselves. The task facing today's breeders and researchers is not to invent pest resistance from scratch, but to understand, strengthen and deliver the natural defences plants have been perfecting since long before the first chemical sprayer was built.

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Crops Growing in Seawater: The Genetic Secret for Saline Soils

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Picture a rice field just a few hundred metres from the sea, its roots standing in water salty enough to kill an ordinary crop within days. This is no longer a hypothetical scene; it is the daily reality for millions of farmers across the world's coastlines and dry interior plains. A landmark global assessment found that nearly 1.4 billion hectares of land, more than a tenth of the Earth's land surface, is now salt-affected, with another billion hectares at risk from climate change and poor land management (FAO, 2024). In the worst-hit regions, salinity can slash yields of staple crops such as rice and beans by up to 70% (FAO, 2024). India alone carries close to 6.7 million hectares of salt-affected soil, concentrated in states such as Gujarat, Uttar Pradesh and West Bengal (FAO, 2024). As groundwater over-extraction, poor drainage and rising seas push more farmland toward salinity, plant breeders and geneticists are asking a bold question: can ordinary crops be taught to grow the way some wild plants already do almost in seawater? The answer lies buried in genes.

When Soil Turns Salty: What Happens Inside a Plant

To appreciate the genetic solutions, it helps to understand what salt actually does to a crop plant. When the soil solution around the roots turns salty, plants face three overlapping problems. The first is osmotic stress: a high salt concentration outside the root makes it harder for the plant to draw in water, so even a well-irrigated, salt-stressed field can behave like a drought (Singh *et al.*, 2024). This "physiological drought" effect shows up within hours of salt exposure, long before any visible injury appears. The second problem is ionic toxicity. As sodium (Na^+) ions flood into root cells, they interfere with potassium (K^+) uptake, disturb enzyme activity, and eventually damage the photosynthetic machinery in leaves once they accumulate in shoot tissue (Singh *et al.*, 2024). Because potassium is essential to hundreds of cellular processes, a cell overloaded with sodium but starved of potassium quickly runs into trouble. The third problem, arising from the first two, is oxidative stress. Disrupted metabolism generates an excess of reactive oxygen species: unstable molecules that damage cell membranes, proteins and DNA (Singh *et al.*, 2024). Ordinary crop plants, technically called glycophytes ("sweet-loving plants"), have only limited natural defences against this triple assault. That is precisely why scientists have turned to a rare group of plants that never got the memo that salt is supposed to be deadly.

Nature's Blueprint: Lessons from Halophytes

Halophytes (plants that complete their life cycle in soils salty enough to kill most crops) make up barely 1–2% of the world's flowering plant species, yet they thrive in coastal marshes, mangrove swamps and inland salt flats (Sasipriya *et al.*, 2026). Species such as Salicornia (glasswort), Puccinellia (alkali grass), and the wild rice relative *Oryza coarctata*, which grows naturally along saline coastlines, have evolved elegant strategies to manage salt rather than simply endure it (Sasipriya *et al.*, 2026). One especially promising halophyte is quinoa (*Chenopodium quinoa*), the Andean grain crop now grown worldwide. Quinoa is what scientists call a "facultative halophyte": it does not need salt to grow, but it tolerates it remarkably well, in part through efficient sequestration of sodium in leaf vacuoles (tiny storage compartments inside plant cells), tight control of potassium levels, and strong antioxidant defences (Hafeez *et al*., 2026). What makes halophytes so valuable to breeders is not that they possess entirely new biology: they largely use the same genes as ordinary crops. The difference lies in how those genes are switched on, how strongly they are expressed, and how well they are coordinated (Sasipriya *et al.,* 2026). In other words, nature has already run the experiment breeders are trying to replicate; the task now is to read the results.

The Genes Behind the Shield

At the heart of salt tolerance lies a small set of genes that control where sodium goes once it enters the plant through the roots. The best studied is the SOS (Salt Overly Sensitive) pathway, in which the gene *SOS1* encodes a pump on the cell membrane that expels excess sodium from root cells back into the soil, or loads it into the plant's internal plumbing (the xylem) for controlled transport (Ali *et al*., 2021). Working alongside *SOS1* is a family of genes called *HKT* (High-affinity K^+ Transporter). Despite their name, *HKT* proteins mainly move sodium, not potassium; they intercept sodium travelling upward in the xylem and unload it before it reaches sensitive young leaves, protecting the photosynthetic tissue that keeps the plant alive (Ali *et al*., 2021). A third key player, *NHX1*, works inside the cell, pumping sodium into the vacuole for safe storage; essentially turning a poison into a tool that helps the cell draw in water osmotically (Hafeez *et al*., 2026).

These transporter genes are themselves controlled by “master switch” genes called transcription factors; proteins that turn entire batteries of stress-response genes on or off. Three families in particular, *DREB, NAC* and *WRKY*, are known to activate networks of salt-responsive genes governing everything from osmotic adjustment to hormone signalling (Singh *et al*., 2024). Understanding this layered system sensor, switch and pump has let scientists identify precisely which genes to track, transfer or edit when breeding for salt tolerance, rather than relying on guesswork.

From Wild Genes to Farmers' Fields: Breeding Success Stories

The clearest proof that this genetic knowledge works lies in rice, a crop especially sensitive to salt at the seedling stage. Decades ago, researchers identified a genetic region on rice chromosome 1, named *Saltol*, that controls seedling-stage salt tolerance largely through the action of the *OsHKT1;5* and *SOS1* genes (Sasipriya *et al*., 2026). This region was traced to a highly tolerant landrace, FL478 and remarkably to genetic contributions from *Oryza coarctata*, the wild salt-tolerant relative of cultivated rice (Sasipriya *et al*., 2026). Using marker-assisted backcross breeding; a technique that uses DNA markers to track and select the Saltol region while retaining all the good traits of a popular variety breeders have introgressed (transferred) Saltol into elite Indian varieties including Pusa Basmati 1, Pusa Basmati 1509, Pusa44 and Sarjoo52, converting salt-sensitive, high-yielding varieties into salt-tolerant ones without sacrificing their quality or yield potential (Singh *et al*., 2018).

India's ICAR–Central Soil Salinity Research Institute (CSSRI) in Karnal has taken this further, releasing more than a dozen salt-tolerant rice varieties; including CSR10, CSR27, the Basmati-quality CSR30, CSR43 and CSR56 that together are now sown across roughly 1.2 million hectares of salt-affected land every cropping season (Gautam *et al*., 2024). Breeders have also begun combining *Saltol* with disease-resistance genes, producing varieties such as CARI Dhan 5 that tolerate both coastal salinity and bacterial blight (Gautam et al., 2024). This kind of “gene pyramiding” stacking multiple beneficial genes into one variety is fast becoming the norm rather than the exception.

The Next Wave: Genomics, Gene Editing and Smarter Breeding

The next generation of salt-tolerant crops will likely be shaped by tools unavailable even a decade ago. Genome-wide association studies (GWAS) and RNA sequencing now let scientists scan the entire genome of hundreds of plant lines at once, pinpointing not just single genes but entire regulatory networks associated with salt tolerance (Singh *et al*., 2024). Genomic selection predicting a plant's field performance directly from its DNA sequence, before it is even sown is compressing breeding cycles that once took a decade into just a few years. Gene-editing tools such as CRISPR now make it possible to fine-tune the activity of genes like *SOS1* or *HKT1* with precision, rather than relying on the slower process of crossing and backcrossing (Sasipriya *et al*., 2026). In polyploid crops such as quinoa, which carries two full sets of chromosomes inherited from different ancestral species, CRISPR can even edit multiple gene copies at the same time something conventional breeding struggles to achieve (Sasipriya *et al*., 2026). Paired with drone-based field sensors that monitor soil salinity and plant stress in real time, breeding programmes are moving toward a data-driven, precision-breeding era.

Conclusion: Why This Matters for Every Farmer

None of this means farmers will soon be irrigating fields with seawater. But the genetic secrets that let quinoa, Salicornia and wild rice relatives thrive in punishing salinity are steadily being decoded, tested and delivered into the varieties farmers actually grow. For a country like India, where salt-affected soils already cover an area larger than several states combined, this is not a distant academic exercise it is a practical route to keeping marginal, salt-hit land productive for the next generation. The lesson from decades of Saltol breeding is an encouraging one: a complex, whole-plant trait like salt tolerance can be captured in a handful of well-understood genes and delivered into farmers' fields without long delays. As genomic tools become cheaper and gene editing more precise, the gap between what a halophyte can do in a salt marsh and what a rice or wheat plant can do in a farmer's field will only keep narrowing.

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Do Happy Fish Swim Differently: The Science of Welfare Monitoring in Aquaculture

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As global aquaculture production surpasses capture fisheries and continues to expand, the welfare of billions of farmed fish has emerged as one of the most pressing ethical and scientific challenges of the twenty-first century. Unlike terrestrial livestock, whose behavioural repertoires and stress responses are comparatively well characterised, fish inhabit an environment that is inherently difficult to observe, and their welfare states remain poorly understood by the public and by many producers. This article reviews the current scientific framework for assessing fish welfare, with particular emphasis on the operational welfare indicators (OWIs) now available to farmers including swimming behaviour, feeding response, respiratory rate, external injuries, stocking density, and abnormal movement patterns. It further examines the transformative potential of computer vision, artificial intelligence, and digital-twin technology to deliver continuous, non-invasive welfare monitoring that could replace periodic, stressful handling events. Drawing on primary research from the FISHWELL project, the Salmon Welfare Index Model (SWIM), the Laksvel protocol, and recent advances in precision fish farming, the article addresses three guiding questions: What does good welfare mean for different aquatic species? Can an algorithm distinguish stress from normal behaviour? And should welfare certification become standard across the aquaculture industry? The evidence suggests that the technological and scientific foundations for robust, species-specific welfare monitoring are now in place, but their widespread adoption will require regulatory leadership, industry investment, and a cultural shift that recognises fish as sentient beings deserving of care.

1.Introduction

The question of whether fish can suffer and, if so, whether we have an obligation to minimise that suffering has moved from the margins of animal ethics into the mainstream of aquaculture science. In 2003, Sneddon, Braithwaite, and Gentle published landmark electrophysiological evidence demonstrating that rainbow trout possess polymodal nociceptors on their heads, establishing that fish have the sensory apparatus necessary for pain perception (Sneddon et al., 2003). A parallel body of behavioural work has since confirmed that fish display cognitively mediated responses to noxious stimuli responses that go well beyond simple reflex arcs and that are modulated by analgesics (Sneddon, 2003; Ashley, 2007). These findings have fundamentally altered the scientific consensus: fish are no longer regarded as insensate automata but as animals whose welfare merits systematic assessment.

The practical implications are enormous. Global aquaculture now produces more food fish than capture fisheries, and the sector continues to grow at roughly 5 - 6 % per year (FAO, 2024). At any given moment, tens of billions of individual fish are held in tanks, ponds, raceways, and sea cages. Yet the industry's capacity to monitor welfare lags far behind that of terrestrial livestock farming, where indicators such as lameness scoring, body condition assessment, and behavioural ethograms have been refined over decades. In aquaculture, the animals are submerged, often in turbid or dimly lit water, and direct observation is limited. Sampling typically requires netting, crowding, and anaesthetization procedures that are themselves stressful and that provide only snapshot data on a single point in time (Noble et al., 2018).

This article therefore has two objectives. First, it reviews the welfare indicators that researchers and the aquaculture industry now use or could use to assess the state of farmed fish, drawing heavily on the FISHWELL handbook (Noble et al., 2018), the Salmon Welfare Index Model (Stien et al., 2013), and the Laksvel protocol (Nilsson et al., 2025). Second, it examines the emerging role of computer vision, artificial intelligence (AI), and digital-twin technology in automating welfare assessment and reducing the need for invasive handling (Noble et al., 2026; Føre et al., 2018). Throughout, three questions guide the discussion: What does good welfare mean for different aquatic species? Can an algorithm distinguish stress from normal behaviour? And should welfare certification become standard in aquaculture?

2. Defining Fish Welfare: Concepts and Frameworks

2.1 What Do We Mean by Welfare?

Animal welfare is not a single, monolithic concept. In a seminal contribution, Broom (1986) defined welfare as ‘the state of an individual as regards its attempts to cope with its environment.’ This coping-based definition directs attention to physiological stress indicators cortisol titre, glucose mobilisation, lactate accumulation and to the biological cost of maintaining homeostasis. A second tradition, rooted in Dawkins’ work on animal preferences, emphasises the subjective experience of the animal: welfare is good when the animal ‘feels well’ and is free from prolonged negative affective states such as pain, fear, and frustration (Huntingford et al., 2006). A third, function-based approach evaluates welfare in terms of biological fitness growth rate, reproductive success, disease resistance on the grounds that an animal functioning well biologically is unlikely to be suffering (Ashley, 2007).

In practice, modern fish-welfare science integrates all three perspectives. The FISHWELL handbook (Noble et al., 2018) explicitly adopts a pluralistic approach, defining good welfare as a state in which the fish is healthy, free from unnecessary suffering, able to express important natural behaviours, and not subjected to conditions that exceed its capacity to cope. This multi-dimensional view is important because different indicators capture different facets of welfare: a fish may have normal cortisol levels but exhibit fin erosion that suggests chronic social stress; conversely, a fish with elevated cortisol may simply be engaged in a brief, adaptive stress response to feeding competition.

2.2 Species-Specific Considerations

A recurring theme in the welfare literature is that ‘one size does not fit all’ Atlantic salmon (*Salmo salar*), the species for which welfare science is most advanced, is an anadromous, cold-water salmonid with complex migratory behaviour and pronounced territorial aggression. Its welfare needs differ markedly from those of European sea bass (*Dicentrarchus labrax*), a gregarious warm-water marine species, or from Nile tilapia (*Oreochromis niloticus*), a hardy freshwater cichlid that tolerates a wide range of environmental conditions (Huntingford et al., 2006; Browman et al., 2019). What constitutes an appropriate stocking density, an acceptable water temperature, or a ‘normal’ swimming pattern is therefore species-dependent and, in some cases, life-stage-dependent. The FISHWELL project produced separate handbooks for Atlantic salmon (Noble et al., 2018) and rainbow trout (Noble et al., 2020), acknowledging that even closely related salmonids require distinct indicator sets.

Browman et al. (2019) further cautioned that extending welfare frameworks developed for teleost fish to other aquatic taxa crustaceans, cephalopods, bivalves require extreme care, because the neuroanatomical and behavioural evidence for sentience varies enormously across phyla. Nevertheless, the direction of travel is clear: as aquaculture diversifies into new species, welfare science must follow, and the development of species-specific indicator toolkits is now a research priority (Noble et al., 2026).

3. Operational Welfare Indicators: The Toolbox

An operational welfare indicator (OWI) is a measurement that is valid (it genuinely reflects some aspect of welfare), reliable (different observers produce consistent scores), practical (it can be applied under farm conditions without specialised laboratory equipment), and fit for purpose (it is appropriate for the species, life stage, and production system in question) (Noble et al., 2018). OWIs are distinguished from laboratory-based welfare indicators (LABWIs), such as plasma cortisol assays or gene-expression profiles, which require samples to be processed off-site and are therefore unsuitable for routine, on-farm monitoring (Noble et al., 2026).

The following subsections review the principal OWIs in current use, organised by the dimension of welfare they address.

3.1 Swimming Behaviour

Swimming behaviour is arguably the most information-rich welfare indicator available to the aquaculturist. Healthy salmon in sea cages typically adopt a circular, polarised schooling pattern, swimming steadily into the current at a speed of roughly one body length per second. Deviations from this baseline loss of polarisation, erratic bursts, surface-seeking (‘jumping’), bottom-dwelling, or prolonged immobility are associated with a range of welfare challenges, including low dissolved oxygen, high temperature, parasitic infection (notably sea lice, *Lepeophtheirus salmonis*), and mechanical injury from cage structures (Stien et al., 2013; Noble et al., 2018).

The Salmon Welfare Index Model (SWIM 1.0) incorporates swimming behaviour as one of its 17 welfare-relevant parameters, weighting it according to its relative impact on the animal’s overall welfare state (Stien et al., 2013). The Laksvel protocol similarly includes group behaviour as one of three group-based indicators, scored on a four-level scale from ‘normal’ (level 0) to ‘severely compromised’ (level 3) (Nilsson et al., 2025). At level 1, minor deviations from normal schooling are recorded; at level 3, the group exhibits grossly abnormal patterns such as widespread lethargy, panic responses, or persistent surface aggregation.

3.2 Feeding Response

Appetite is one of the earliest and most sensitive indicators of compromised welfare. Fish that are stressed, diseased, or in pain typically reduce or cease feeding, a response that is mediated by the hypothalamic–pituitary–interrenal (HPI) axis and by the suppressive effects of cortisol on appetite centres in the brain (Ashley, 2007). On commercial farms, feeding response is routinely monitored by trained operators who observe the intensity and duration of surface activity during feeding events and adjust feed delivery accordingly.

The SWIM model includes appetite as a dedicated indicator, assessed as the proportion of expected daily ration actually consumed (Stien et al., 2013). The Laksvel protocol adopts a similar approach, recording appetite as one of three group-based OWIs (Nilsson et al., 2025). In both systems, a sustained decline in appetite triggers a welfare alert and prompts investigation of potential causes, including environmental deterioration, disease onset, or equipment malfunction.

Recent advances in computer vision have made it possible to automate the assessment of feeding behaviour. Li et al. (2020) reviewed the application of deep-learning algorithms to recognise feeding intensity from underwater video, demonstrating that convolutional neural networks (CNNs) can classify feeding activity with accuracies exceeding 90 %. Such systems have the potential to replace subjective human observation with objective, continuous, and quantifiable measurements, thereby improving both the sensitivity and the consistency of feeding-response monitoring (Noble et al., 2026).

3.3 Respiratory Rate

The frequency of opercular (gill-cover) movements provides a direct, real-time measure of respiratory effort. In teleost fish, opercular beat rate (OBR) increases in response to hypoxia, elevated temperature, gill disease, and acute stress, making it a valuable physiological welfare indicator (Ashley, 2007). Under controlled laboratory conditions, OBR can be measured precisely using electrodes or laser-based sensors, but such methods are impractical in commercial sea cages or ponds.

Computer vision offers a non-invasive alternative. High-resolution underwater cameras, combined with AI-powered image analysis, can now detect the rhythmic opening and closing of the operculum and estimate respiratory frequency without physical contact with the fish. Pilot studies have demonstrated the feasibility of this approach in laboratory tanks and small-scale cages, although significant technical challenges remain including image resolution at distance, occlusion by neighbouring fish, and the computational cost of processing high-frame-rate video in real time (Noble et al., 2026; Føre et al., 2018).

3.4 External Injuries and Morphological Condition

Physical injuries scale loss, skin lesions, fin erosion, eye damage, snout wounds, and opercular deformities are among the most widely used individual-based OWIs in salmonid aquaculture. The FISHWELL handbook provides standardised photographic scoring guides for each injury type, using a four-level scale (0 = no damage; 3 = severe damage) to ensure consistency between observers (Noble et al., 2018). The Laksvel protocol incorporates 14 individual-based indicators, many of which relate to external morphological condition (Nilsson et al., 2025).

Injuries are informative not only because they reflect past or ongoing welfare challenges such as aggression, handling damage, predator attacks, or parasite infestation but also because they predispose the fish to secondary infections. Scale loss, for example, compromises the skin's barrier function and increases susceptibility to opportunistic pathogens. Fin erosion, which is often associated with high stocking density and poor water quality, is a particularly well-studied indicator and has been shown to correlate with elevated cortisol levels and reduced growth in Atlantic salmon (Turnbull et al., 2005; Noble et al., 2018).

3.5 Stocking Density and Crowding

Stocking density typically expressed as kilograms of fish per cubic meter of water is both an environmental parameter and a welfare determinant. At excessive densities, fish experience increased competition for feed, reduced water quality (through oxygen depletion and ammonia accumulation), higher rates of fin damage and scale loss and disrupted social hierarchies (Turnbull et al., 2005). The relationship between density and welfare is, however, non-linear and context-dependent: the same density may be acceptable in a well-oxygenated, high-flow site but damaging in a sheltered, low-flow location.

Turnbull et al. (2005) used multivariate analysis to demonstrate that welfare outcomes in Atlantic salmon are determined by the interaction of stocking density with multiple environmental variables, rather than by density alone. This finding has informed regulatory approaches in several jurisdictions: rather than setting a single maximum density, best-practice guidelines now require that density be managed in conjunction with water quality monitoring, feeding strategy, and health surveillance (Noble et al., 2018; Nilsson et al., 2025).

3.6 Abnormal Movements and Stereotypies

Abnormal repetitive behaviours sometimes termed stereotypies are well-established indicators of compromised welfare in terrestrial animals, but their occurrence and significance in fish have received comparatively little attention. In aquaculture settings, abnormal movements may include persistent circling in one direction, head-shaking, jaw-gaping, flashing (rapid lateral rolling, often associated with ectoparasite irritation), and 'panic' responses such as sudden bursts of high-speed swimming followed by collision with cage structures (Noble et al., 2018; Stien et al., 2013).

The interpretation of abnormal movements requires caution. Some behaviours that appear 'abnormal' to a human observer may be functionally adaptive: flashing, for example, may help to dislodge parasites, and surface jumping may facilitate gas-bladder adjustment or ectoparasite removal. Nevertheless, a high frequency of such behaviours within a population is generally regarded as evidence of a welfare challenge that warrants investigation (Noble et al., 2018; Huntingford et al., 2006).

4. Technology-Enabled Welfare Monitoring

4.1 The Case for Continuous, Non-Invasive Observation

The traditional approach to welfare assessment in aquaculture is episodic and invasive. Fish are periodically netted, crowded into a smaller volume, and either examined in situ or sampled for laboratory analysis. Each such event imposes a measurable stress response elevated cortisol, increased heart rate, disrupted swimming behaviour that may itself compromise welfare and confound the very measurements it is intended to obtain (Noble et al., 2018). Moreover, episodic sampling provides only a snapshot: welfare challenges that develop between sampling events may go undetected until they have progressed to the point of clinical disease or mortality.

The aspiration, therefore, is to develop monitoring systems that observe fish continuously, non-invasively, and in real time analogous to the closed-circuit television (CCTV) systems used in terrestrial livestock housing but adapted to the unique challenges of the aquatic environment (Føre et al., 2018; Noble et al., 2026). Such systems would ideally capture multiple welfare indicators simultaneously swimming speed, schooling structure, feeding response, respiratory rate, and external condition and present them to the farmer as an integrated welfare dashboard.

4.2 Computer Vision and Artificial Intelligence

Computer vision (CV) is the enabling technology for this ambition. Underwater cameras, now routinely installed in salmon sea cages for biomass estimation and lice counting, generate vast quantities of video data that, until recently, could be interpreted only by human observers. The advent of deep learning algorithms particularly convolutional neural networks (CNNs) and object detection architectures such as YOLO (You Only Look Once) has made it possible to automate the extraction of behavioural information from video at speeds and scales that far exceed human capacity (Noble et al., 2026).

Recent applications include: (i) automated tracking of individual fish or schools, enabling the computation of swimming speed, trajectory, and inter-individual distances; (ii) detection and classification of external injuries such as scale loss, skin lesions, and fin damage, using image classifiers trained on annotated photographic libraries; (iii) estimation of opercular beat rate from high-frame-rate video; and (iv) classification of feeding intensity from the spatial and temporal dynamics of fish aggregation at the surface during feed delivery (Li et al., 2020; Noble et al., 2026).

The critical question "Can an algorithm distinguish stress from normal behaviour?" is now being answered affirmatively in controlled settings. Studies have demonstrated that machine-learning classifiers can distinguish between 'normal' and 'stressed' swimming patterns with accuracies exceeding 85-90 % when trained on labelled datasets from experimental exposures to known stressors (e.g., hypoxia, crowding, thermal challenge). The challenge, however, lies in generalisation: models trained on one species, age class, or environmental context may not transfer reliably to another (Noble et al., 2026). Building robust, species-specific training datasets is therefore a prerequisite for the deployment of AI-based welfare monitoring at commercial scale.

4.3 Digital Twins and Integrated Decision Support

The concept of the 'digital twin' a virtual replica of a physical system, continuously updated with real-time sensor data offers an integrative framework for welfare monitoring that goes beyond any single indicator. In the context of aquaculture, a digital twin of a sea cage or recirculating aquaculture system (RAS) would assimilate data from environmental sensors (temperature, oxygen, salinity, current), biomass cameras, feeding systems, and AI-powered behavioural analysis to construct a dynamic model of the welfare state of the fish population (Noble et al., 2026).

Noble et al. (2026) describe how such a system could operate within the Precision Fish Farming (PFF) framework proposed by Føre et al. (2018), which conceptualises farm management as a cyclical process of Observe → Interpret → Decide → Act. The digital twin would handle the first two steps observing and interpreting by fusing multi modal data streams into a unified welfare assessment. The farmer (or an automated control system) would then decide on corrective actions (e.g., reducing feed delivery, increasing water flow, initiating a delousing treatment) and act accordingly. Over time, the digital twin would learn from the outcomes of these actions, improving its predictive accuracy and enabling proactive, rather than reactive, welfare management.

While fully operational digital twins for fish welfare remain largely aspirational, the component technologies environmental sensing, underwater imaging, AI-based behavioural analysis, and cloud-based data integration are individually mature or maturing rapidly. The principal barriers to deployment are not technological but organisational: data standardisation, interoperability between proprietary systems, and the development of validated welfare algorithms for multiple species and production contexts (Noble et al., 2026; Føre et al., 2018).

5. From Laboratory to Sea Cage: Pilot Studies and Field Validation

The transition from laboratory proof-of-concept to operational deployment in commercial aquaculture is fraught with challenges. Underwater environments present formidable imaging obstacles: variable and often low light levels, particulate matter and biofouling that degrade camera lenses, strong currents that displace cameras and alter fish behaviour, and the sheer density of fish in commercial cages, which creates occlusion problems for tracking algorithms (Noble et al., 2026).

Nevertheless, pilot studies are demonstrating the feasibility of minimally invasive monitoring systems in commercial settings. In Norway, where the salmon industry has been at the forefront of welfare innovation, underwater cameras are now standard equipment in sea cages, and several technology companies have developed commercial CV systems for lice counting and biomass estimation. Extending these systems to welfare monitoring is a natural and, increasingly, an economically attractive next step (Føre et al., 2018; Noble et al., 2026).

Feeding-recognition research has been particularly productive. Automated systems that detect the onset, intensity, and cessation of feeding activity are now in commercial use, enabling farmers to optimise feed delivery and reduce waste. These systems provide a template for welfare-oriented CV, demonstrating that cameras can interpret complex fish behaviour with sufficient accuracy to inform management decisions (Li et al., 2020; Noble et al., 2026).

Arechavala-Lopez and colleagues have contributed to a growing body of work on underwater behavioural monitoring, emphasising the potential of AI-powered video analysis to provide continuous, 24/7 welfare assessments without the invasive handling required by traditional methods such as acoustic telemetry or manual sampling (Arechavala-Lopez et al., 2022). Their research on environmental enrichment further highlights the role of behavioural data captured by modern surveillance systems in evaluating the effectiveness of welfare interventions.

6. Can an Algorithm Distinguish Stress from Normal Behaviour?

This question lies at the heart of technology-enabled welfare monitoring and deserves careful examination. The answer, in short, is: increasingly yes, but with important caveats.

On the positive side, deep-learning models have demonstrated impressive performance in classifying behavioural states in controlled experiments. Models trained on video data from Atlantic salmon exposed to standardized stressors acute hypoxia, crowding events, thermal ramping can reliably identify the transition from normal schooling to disorganised, high-speed, or lethargic swimming. Similarly, feeding-intensity classifiers can detect the difference between vigorous, 'normal' feeding and the suppressed, tentative feeding that characterises stressed or diseased fish (Li et al., 2020; Noble et al., 2026).

On the cautionary side, several challenges remain. First, stress is not a unitary phenomenon. A fish may exhibit acute stress (a rapid cortisol surge in response to a handling event), chronic stress (a sustained elevation of baseline cortisol due to poor environmental conditions), or allostatic overload (a breakdown of the stress-response system itself). Each of these states may produce different and potentially overlapping behavioural signatures (Huntingford et al., 2006; Ashley, 2007). Second, 'normal' behaviour is itself variable: it depends on species, age, time of day, season, feeding state, and social context. An algorithm trained on one context may misclassify behaviour in another. Third, the ground-truth labelling of training data is often based on human expert judgement, which is itself subjective and may embed biases.

Despite these challenges, the trajectory is encouraging. Multimodal approaches combining video data with environmental sensor data (temperature, oxygen, current) and biological data (feeding records, mortality logs) are improving classification accuracy by providing the algorithm with contextual information that helps to disambiguate behavioural signals. The integration of such multimodal data streams within a digital-twin framework offers the most promising path toward algorithms that can reliably detect welfare compromise under real-world conditions (Noble et al., 2026; Føre et al., 2018).

7. Should Welfare Certification Become Standard in Aquaculture?

The final question addressed by this article is normative as well as scientific: should welfare certification become a standard requirement for aquaculture products, analogous to the organic, free-range, and animal-welfare certifications now commonplace in terrestrial livestock production?

The scientific case for certification rests on three pillars. First, robust, validated welfare indicators are now available for at least the major farmed species Atlantic salmon, rainbow trout, European sea bass, gilthead sea bream and standardized protocols such as Laksvel (Nilsson et al., 2025) provide a practical framework for on-farm assessment. Second, technology is increasingly capable of delivering the continuous, objective monitoring that certification schemes require: computer vision can generate auditable records of welfare performance over time, rather than relying on the subjective impressions of a single inspector on a single visit (Noble et al., 2026). Third, consumer awareness of fish welfare is growing, and market research suggests that a significant proportion of consumers are willing to pay a premium for welfare-certified seafood (Browman et al., 2019).

The practical challenges, however, are considerable. Welfare standards must be species-specific, production-system-specific, and life-stage-specific, which makes the development of universal certification criteria extremely complex. Enforcement is difficult in a globalised industry where production occurs in jurisdictions with widely varying regulatory capacity. And the cost of implementing monitoring technology cameras, sensors, AI platforms, data storage may be prohibitive for small-scale producers in developing countries, who are responsible for a large share of global aquaculture output.

Nevertheless, the direction of travel is clear. The European Union's Directorate-General for Health and Food Safety has signalled its intention to include fish welfare within future revisions of animal-welfare legislation. Norway, the world's largest producer of farmed Atlantic salmon, has already implemented mandatory welfare monitoring through its Animal Welfare Act and associated regulations. Several private-sector certification schemes including the Aquaculture Stewardship Council (ASC) and Global G.A.P. now include fish-welfare criteria in their standards, although the rigour and enforceability of these criteria vary.

The most compelling argument for standardised welfare certification is, ultimately, an ethical one. If the scientific evidence demonstrates that fish are sentient beings capable of suffering and the weight of evidence now strongly supports this conclusion (Sneddon et al., 2003; Huntingford et al., 2006) then the industry has a moral obligation to minimise that suffering, and consumers have a right to know whether the products they purchase have been produced in accordance with acceptable welfare standards. Certification, supported by technology-enabled monitoring, is the most practical mechanism for delivering on both of these obligations.

8. Conclusions and Future Directions

The science of fish welfare has matured dramatically over the past two decades. We now have a robust conceptual framework for defining and measuring welfare, a growing toolkit of operational welfare indicators validated for the major farmed species, and emerging technologies computer vision, artificial intelligence, digital twins that promise to transform welfare monitoring from an episodic, invasive, and subjective exercise into a continuous, non-invasive, and data-driven process.

To the three questions posed at the outset of this article, the following answers can now be offered:

What does good welfare mean for different aquatic species? Good welfare is a multi-dimensional state that encompasses physical health, the ability to perform key natural behaviours, and the absence of prolonged negative subjective experiences. Its definition and measurement are necessarily species-specific: what is good for salmon is not necessarily good for tilapia, and welfare science must continue to develop tailored indicator sets for each major farmed species.

Can an algorithm distinguish stress from normal behaviour? Increasingly, yes particularly when multimodal data streams (video, environmental sensors, biological records) are integrated within machine-learning frameworks. However, robust generalisation across species, life stages and production contexts remains a challenge, and the field urgently needs large, well-annotated, publicly available training datasets.

Should welfare certification become standard in aquaculture? The scientific, ethical, and market driven arguments all point toward yes. The technological tools for credible, auditable welfare monitoring are now within reach. What is needed is regulatory ambition, industry collaboration, and a willingness to invest in the welfare of animals that, despite their evolutionary distance from us, are unambiguously capable of suffering. The fish in our care cannot tell us how they feel. But they can show us through their swimming, their feeding, their breathing, and their injuries. It is our responsibility, as scientists and as stewards, to watch, to listen, and to act.

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Green Nanotechnology: Harnessing Medicinal Plants for Sustainable Agriculture

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Nanotechnology is the science and technology of utilizing particles ranging in size from 1 to 100 nanometers (1 nm = 10^{-9} m). These nanoparticles possess unique physical and chemical properties that distinguish them from their bulk counterparts. Common types of nanoparticles include metal nanoparticles (such as silver and gold), metal oxide nanoparticles (such as zinc oxide, titanium dioxide, and iron oxide), carbon-based nanoparticles (such as carbon nanotubes, graphene, and fullerenes), polymeric nanoparticles, lipid-based nanoparticles, and quantum dots.

Nanoparticles are characterized by their large surface area, high reactivity, mechanical strength, sensitivity, and stability. Their functional properties include transparency, hydrophobicity, photoluminescence, chemical sensitivity, and bioavailability. These unique characteristics arise primarily from their high surface area-to-volume ratio. Nanoparticles (NPs) have wide-ranging applications in agriculture, plant biotechnology, medicine, electronics, and various industrial sectors. In agriculture and plant biotechnology, nanoparticles have shown significant potential to enhance seed germination, promote plant growth, and improve photosynthetic efficiency. They have also been demonstrated to function as safe and effective nano-pesticides and nano-fertilizers, contributing to sustainable crop production.

Nanoparticles Derived from Medicinal Plants

Medicinal plants are widely used for the green synthesis of nanoparticles because they provide a sustainable and environmentally friendly approach. They are rich sources of secondary metabolites such as flavonoids, alkaloids, phenolic compounds, terpenoids, and proteins, which play a crucial role in the green synthesis of nanoparticles. Biologically active compounds present in various plant parts, including leaves, roots, bark, seeds, and flowers, act as reducing, stabilizing, and capping agents during nanoparticle synthesis. These plant-derived compounds facilitate the formation of nanoparticles through a single-step process, making the synthesis efficient and eco-friendly. This biological synthesis method is simple, cost-effective, and eliminates the need for toxic chemicals. Commonly synthesized nanoparticles using medicinal plants include silver nanoparticles (AgNPs), zinc oxide nanoparticles (ZnO-NPs), iron oxide nanoparticles (Fe_3O_4-NPs), copper oxide nanoparticles (CuO-NPs), and gold nanoparticles (AuNPs).

Characterization of Nanoparticles

The composition, size, shape, structure, and surface properties of nanoparticles are determined using various characterization techniques. These techniques are employed to accurately evaluate the physical and chemical properties of nanoparticles. Common characterization techniques include Ultraviolet–Visible (UV–Vis) Spectroscopy, X-ray Diffraction (XRD), Scanning Electron Microscopy (SEM), Transmission Electron Microscopy (TEM), Atomic Force Microscopy (AFM), Dynamic Light Scattering (DLS), Fourier Transform Infrared Spectroscopy (FTIR), Zeta Potential Analysis, Energy Dispersive X-ray Analysis (EDX), and Brunauer–Emmett–Teller (BET) Surface Area Analysis. These techniques provide comprehensive information on the morphology, crystallinity, particle size, elemental composition, surface chemistry, stability, and specific surface area of nanoparticles.

Impact of Nanoparticles on Plant Growth and Protection

Nanoparticles serve as environmentally friendly alternatives to conventional fertilizers and pesticides, thereby enhancing agricultural productivity and sustainability. Plant-derived nanoparticles improve seed germination, root elongation, and shoot growth by enhancing nutrient uptake, water absorption, and metabolic activities. For example, zinc oxide (ZnO) and iron (Fe) nanoparticles stimulate chlorophyll synthesis and photosynthetic efficiency, leading to improved plant growth and development. Nanoparticles also function as nano fertilizers, increasing the availability and uptake of essential nutrients such as zinc, iron, and copper. This improves nutrient use efficiency while reducing fertilizer losses. Nanoparticles synthesized from medicinal plants enhance chlorophyll content, photosynthetic rate, and stomatal conductance, resulting in increased plant biomass and crop yield. Furthermore, these nanoparticles improve plant tolerance to abiotic stresses such as drought, salinity, and heavy metal toxicity by enhancing the activity of antioxidant enzymes, including superoxide dismutase (SOD), catalase (CAT), and peroxidase (POD). Medicinal plant-derived silver (AgNPs) and copper nanoparticles (CuNPs) also exhibit strong antibacterial and antifungal properties, helping to suppress plant diseases and reduce dependence on chemical pesticides. This eco-friendly approach supports sustainable crop production while minimizing environmental pollution and chemical inputs.

Advantages

- Environmentally friendly and supports sustainable agriculture.
- Cost-effective method of nanoparticle synthesis and application.
- Reduces the use of chemical fertilizers and pesticides, thereby minimizing environmental pollution.
- Enhances crop productivity and improves soil health.

Limitations and Challenges

- High nanoparticle concentrations may cause phytotoxicity, adversely affecting plant growth and development.
- The long-term environmental impacts of nanoparticles are not yet fully understood and require further investigation.
- Standardized application protocols, safety assessments, and large-scale field studies are needed before their widespread agricultural adoption.

Conclusion

Nanoparticles synthesized from medicinal plants represent a sustainable, cost-effective, and environmentally friendly approach to addressing several challenges in modern agriculture. These plant-derived nanoparticles play a significant role in enhancing plant growth, crop yield, nutrient use efficiency, and tolerance to biotic and abiotic stresses. With appropriate standardization, safety evaluation, and optimized application strategies, medicinal plant-derived nanoparticles have great potential to become an effective tool for sustainable and climate-resilient agriculture, reducing dependence on synthetic agrochemicals while improving crop productivity and environmental health.

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Urban Agriculture and Vertical Farming: Transforming the Future of Food Production

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Rapid urbanization, population growth, shrinking agricultural land, and climate change are creating significant challenges for global food production. According to the United Nations, nearly 70% of the world's population is expected to live in urban areas by 2050. This shift demands innovative approaches to ensure a steady supply of fresh, nutritious, and sustainable food. Urban agriculture and vertical farming have emerged as promising solutions that bring food production closer to consumers while making efficient use of limited resources. Urban agriculture is the practice of cultivating, processing, and distributing food within and around cities. Vertical farming is an advanced form of urban agriculture where crops are grown in stacked layers using controlled environment agriculture (CEA). Together, these farming systems have the potential to improve food security, reduce transportation costs, conserve natural resources, and create greener cities.

What is Urban Agriculture?

Urban agriculture refers to the cultivation of crops, raising of livestock, aquaculture, and related agricultural activities within urban and peri-urban areas. Unlike conventional farming, urban agriculture utilizes rooftops, balconies, vacant plots, community gardens, school campuses, warehouses, and even indoor spaces for food production. The primary objective is to produce fresh food close to consumers while improving environmental sustainability and strengthening local food systems.

Types of Urban Agriculture

1. Home Gardens: Many households cultivate vegetables, fruits, herbs, and ornamental plants in backyards, terraces, balconies, or kitchen gardens.

2. Community Gardens: Local residents collectively manage gardens on public or private land, producing vegetables while promoting social interaction and environmental awareness.

3. Rooftop Farming: Unused rooftops are converted into productive spaces for growing vegetables, herbs, flowers, and fruits using containers or raised beds.

4. Indoor Farming: Controlled environments such as warehouses, greenhouses, and shipping containers are used to grow crops year-round.

5. Aquaponics and Hydroponics: These soils-less cultivation methods enable efficient production of vegetables in urban settings with limited space.

Benefits of Urban Agriculture

Improved Food Security

Urban agriculture provides fresh produce throughout the year, reducing dependence on distant food supply chains and enhancing local food availability.

Better Nutrition

Consumers gain easy access to fresh vegetables, fruits, and herbs with minimal storage and transportation losses.

Environmental Benefits

Urban farming helps reduce urban heat islands, improve air quality, absorb carbon dioxide, increase biodiversity, and manage rainwater runoff.

Employment Generation

Urban agriculture creates income opportunities through production, processing, marketing, and value-added enterprises.

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Waste Recycling

Kitchen waste, compost, and treated wastewater can be recycled effectively for crop production, reducing landfill burden.

Community Development

Community gardens encourage cooperation, education, recreation, and awareness about healthy lifestyles.

Challenges in Urban Agriculture

Despite its advantages, urban agriculture faces several constraints *viz;* limited land availability, high land prices, water scarcity, soil contamination in urban areas, lack of technical knowledge ,pest and disease management ,regulatory restrictions and Initial investment costs. This issue can be addressed with vertical farming.

What is Vertical Farming?

Vertical farming is an innovative agricultural technique in which crops are grown vertically in stacked layers inside buildings or specially designed structures. Crops are cultivated under carefully controlled environmental conditions using artificial lighting, precise irrigation, and climate control systems.Unlike traditional farming, vertical farms are independent of weather conditions and seasonal variations, allowing year-round production.

Key Technologies Used

- Hydroponics

  Plants grow without soil using nutrient-rich water solutions. Hydroponics significantly reduces water consumption while promoting rapid plant growth.

- Aeroponics

  Plant roots remain suspended in air and receive nutrients through fine nutrient mist sprays. This technique uses very little water and provides excellent oxygen supply.

- Aquaponics

  Aquaponics combines hydroponics with fish farming. Fish waste provides nutrients for plants, while plants naturally filter the water before it returns to the fish tanks.

- LED Lighting

  Energy-efficient LED lights provide the precise wavelengths required for photosynthesis, allowing plants to grow indoors without sunlight.

- Climate Control

  Temperature, humidity, carbon dioxide concentration, and airflow are continuously monitored and adjusted to maximize crop productivity.

- Automation and Artificial Intelligence

  Modern vertical farms use sensors, robotics, drones, and AI-based monitoring systems to optimize irrigation, nutrient delivery, pest detection, and harvesting.

Advantages of Vertical Farming

- Higher Productivity: Multiple stacked layers produce significantly more food per unit area compared to conventional farming.
- Year-Round Production: Controlled environments eliminate dependence on seasonal weather, ensuring continuous crop production.
- Water Conservation: Hydroponic and aeroponic systems use up to 90–95% less water than traditional agriculture by recycling water within the system.
- Reduced Land Requirement: Vertical farming requires only a small land footprint, making it ideal for densely populated urban areas.
- Minimal Pesticide Use: Indoor cultivation protects crops from many pests and diseases, reducing the need for chemical pesticides.
- Reduced Transportation: Food is produced close to consumers, lowering transportation costs,

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reducing fuel consumption, and minimizing carbon emissions.

- Better Food Quality: Fresh vegetables reach consumers quickly, retaining higher nutritional value and freshness.

Limitations of Vertical Farming

Vertical farming also has certain drawbacks and constraints apart from its promising returns

- High Initial Investment: Construction, lighting, climate control, automation, and monitoring systems require substantial capital investment.
- High Energy Consumption: Artificial lighting and climate control systems increase electricity demand, especially in regions with high energy costs.
- Limited Crop Diversity: Currently, leafy vegetables, herbs, strawberries, and microgreens are the most economically viable crops. Large cereals such as rice, wheat, and maize are generally unsuitable for vertical farming.
- Technical Expertise: Operating advanced controlled environment systems requires skilled personnel with knowledge of engineering, plant science, and data management.

Suitable Crops for Vertical Farming**:** Vertical farming is particularly suitable for Lettuce, Spinach, Kale, Basil, Mint, Coriander, Parsley, Microgreens ,Tomatoes ,Cucumbers Strawberries and Peppers. These crops have relatively short growth cycles and high market demand.

Urban Agriculture and Vertical Farming in India

India is witnessing growing interest in urban farming due to increasing urban populations and rising demand for safe, pesticide-free vegetables. Several startups, research institutions, and entrepreneurs are developing innovative hydroponic and vertical farming systems. Major metropolitan cities such as Bengaluru, Hyderabad, Mumbai, Delhi, Chennai, and Pune have seen rapid adoption of rooftop gardens, hydroponic farms, and indoor vertical farming units. Government initiatives promoting protected cultivation, precision farming, startup innovation, and smart cities are also encouraging urban agriculture. Educational institutions and agricultural universities are increasingly conducting research and training programs on controlled environment agriculture.

Environmental and Social Impact

Modern urban agriculture relies heavily on digital technologies, include Internet of Things (IoT) sensors, Artificial Intelligence (AI),Machine learning, Remote monitoring, Automated irrigation systems ,Nutrient management software ,Robotics for harvesting, Drone-based monitoring, Renewable energy integration and Data analytics for crop optimization. These technologies improve productivity while reducing labor requirements and operational costs.

Urban agriculture contributes to sustainable city development by reducing greenhouse gas emissions associated with long-distance transportation, improving urban biodiversity, enhancing green cover, and promoting efficient resource use. Community gardens foster social cohesion, provide educational opportunities, and encourage healthier eating habits. Vertical farming further supports sustainability through efficient water use, reduced pesticide application, and year-round local food production, although its environmental benefits depend on access to clean and renewable energy sources.

Future Prospects

The future of urban agriculture and vertical farming appears highly promising. Advances in renewable energy, artificial intelligence, automation, biotechnology, and precision agriculture are expected to improve efficiency and reduce production costs. As climate change intensifies and urban populations continue to grow, these systems will play an

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increasingly important role in strengthening food security.

Future developments may include f ully automated smart farms,Solar-powered vertical farming systems,AI-driven crop management,Integration with smart city infrastructure ,Expansion of rooftop farming networks ,Greater adoption of hydroponics and aquaponics in schools and communities and Improved policies and financial support for urban farming initiatives

Conclusion

Urban agriculture and vertical farming represent a new era of sustainable food production. By utilizing limited urban spaces efficiently and embracing advanced technologies, these systems offer practical solutions to challenges such as food insecurity, climate change, resource scarcity, and rapid urbanization. While high investment and energy requirements remain important considerations, continuous technological advancements and supportive government policies are making these farming methods increasingly viable.

For countries like India, where urban populations are expanding rapidly, urban agriculture and vertical farming can complement conventional agriculture by supplying fresh, nutritious produce closer to consumers, reducing environmental impacts, and creating new employment opportunities. As cities continue to grow, these innovative farming practices will become integral components of resilient, sustainable, and climate-smart food systems.

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Smart Packaging of fruits to monitoring its quality

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Intelligent packaging for fresh food is a groundbreaking technique aimed at minimizing waste and safeguarding consumer health and safety. Intelligent packaging solutions further assist in extending the longevity of perishable goods during transportation and bulk storage, which are usually challenging to manage. The use of these always advancing technologies in fruit packaging may provide several beneficial outcomes, such as enhanced fruit quality, less waste, and therefore better public health. This article analyses the function of intelligent packaging in fruit packaging, the existing advancements, obstacles, initially, we examine the rationale for monitoring and maintaining fruit quality, then addressing the developmental history of fruits, the criteria for assessing fruit quality, and the categorization of intelligent packaging systems. Then, we discuss conventional freshness sensors for packaged fruits including direct and indirect freshness indicators. After that, we provide examples of possible smart packaging systems and sensors that can be used in monitoring fruits quality, followed by several strategies to mitigate premature fruit decay, and active packaging technologies. Finally, we discuss the prospects of smart packaging application for fruit quality monitoring along with the associated challenges and prospects.

Introduction

Present civilization has an extreme urgency of innovation in the field of food production, storage, and distribution to solve hunger problems that still afflict several parts of the world. Food production is rapidly growing with the help of science and technology due to increased demand. However, there is a large disparity between the different countries where there are constant food shortages and some other countries where food is wasted at an alarming rate. The global food market has a higher than ever demand to deliver fresher, higher quality food at a reasonable cost with a global population of 7.6 billion producing over 1.3 billion tonnes of food wastage, and a projected population of 9.6 billion by 2050 current food processing practices and technologies must be assessed and improved. Fruits and vegetables are living biological bodies, having a respiratory system that continues during their living processes and even after harvest. By respiration, fruits and vegetables take in oxygen and give out carbon dioxide. Therefore, the handling and packaging of fruits are key toward maintaining their freshness until they reach the consumer's table. One of the major sources of premature spoilage in perishable fruits is during transport and storage. This is a key issue for fresh fruits, which gets very little quality monitoring after it has been harvested, treated, and packed. Fruits are necessary parts of the human diet, as they contain vitamins, minerals, antioxidants, fiber, and many other essential nutrients. Due to the potential severity of these hazards, regulations on fresh fruits are stringent, particularly in the developed countries. Resellers take precautionary measures such as disposing of food that has passed its "best before" date, which the United States Department of Agriculture states is not a true indicator of spoiled food. Conventional packaging aims to limit the harmful environmental exposure of fruits and fruit products, but it is often not enough. It is difficult to monitor and retain the peak level of quality during all stages of food processing. In most cases, the fruit may not have warning about problems before it is too late. To address this need in produce processing, along with other food-processing innovations, freshness sensors and smart packaging system for fruit monitoring have emerged. Fruit freshness sensors or indicators can sense and inform the status of a fruit's quality, such as freshness, ripeness, leak, microbial pathogens, and emitted gases, correlated to the safety of the food being consumed. Therefore, the freshness sensors can be defined as the on-package sensors or indicators that can sense the freshness of the food associated to the environment inside or outside of the package and advise about the quality and safety of the food. On the other hand, smart packaging systems offer methods for both passive and active packaging solutions. Embedded with sensor technology that can detect changes in fruits' health and environmental conditions that impact quality, intelligent packaging allows for the use of real-time monitoring until the product is delivered to the customer. In fact, smart packaging systems can be further applied to create response systems that can mitigate spoilage conditions and prolong the shelf-life of perishable items. While still in its early stages, the numerous opportunities for the applications of smart packaging technology in spoilage prevention for fruits is a key motivator for further research and development.

Smart Packaging Systems for Fruit Freshness

Freshness sensors or indicators can sense and inform about the quality of fruits in terms of their freshness level, ripeness, or firmness. Therefore, fruit freshness sensors are on-package indicators that monitors the environment inside or outside the package and allow consumers to make informed decisions about the quality of the fruits On the other hand, smart packaging and/or sensors refer to an embedded system, which is a combination of electronics and electrochemical/electro-optical sensors that are near packaged fruits, allowing continuous monitoring of the quality of packaged fruits once the package leave the plant until it reaches to consumers. The use of freshness sensors in fruits' packaging vastly depends on the type of fruits and the fruits physiology. Smart Packaging describes the embedded systems technology used in product packaging. Traditional commercial packaging does not possess the ability to monitor the quality of the product once it has left the packaging plant. Smart packaging allows us to continue to monitor and maintain quality all the way until the product is consumed. Smart systems can vary from simple self-contained units to fully integrated subsystems interacting together to perform multiple tasks.

Intelligent Systems in Fruit Packaging

Smart packaging solutions utilize a variety of sensor technologies to recognize and resolve problems in fruit packaging. Different sensors may be used depending on the type of fruit being monitored. This subsection of the review describes the common freshness sensors used for packaged fruits. There are two types of freshness sensors one is direct sensors and another one indirect sensors. As the name suggests, a direct freshness sensor detects a particular analyte directly from the fruit as an indicator for food freshness. On the other hand, an indirect freshness sensor is based on indirect or reaction-based detection of fruits degradation due to certain freshness parameters such as temperature and/or time. These sensors are uniquely designed based on different stages of monitoring such as the food distribution chains and consumer package on the shelf. In any case, the sensors should correctly monitor the rate of deterioration of fruit freshness an array of concepts for fruit freshness sensors or indicators have been developed including aldehyde, volatile organic compounds (VOC), ethanol, hydrogen sulfide (H_2S), pH, and CO_2. The sensors or indicators are integrated into the food package as a visible indicator, label, or tag that undergoes color changes according to changes in the freshness markers and/or analytes. Freshness sensors can consist of single, dual, or multiple sensors array. Most commercial freshness sensors utilize a single sensor. Single sensors can only monitor one freshness parameter at a time, such as pH or time-temperature. Dual freshness sensors use two sensors that reference each other in the sensing process while informing food freshness at the same time. However, dual, and multiple sensor array architectures are being developed at the lab scale and will soon be available in the market.

MAP (Modified atmosphere packaging)

In many conditions of processed fruit packaging, modified atmosphere packaging (MAP) and equilibrium MAP are very useful, which require gas sensors to indicate fruit freshness. The atmosphere in MAP typically consists of lower O_2 level (~2%) and higher CO_2 level (20%–80%). Two major types of MAPs are passive and active MAPs. Passive MAP depends on produce respiration and permeability of the packaging material, which establishes an equilibrium atmosphere inside the MAP. For example, fresh cut apples stored at 2°C showed that the O_2 content decreased from 21% (first hour) to 6.89% (190 h), and the CO_2 content increased from 0.02% to 7.98%; after that, the concentration became almost constant or equilibrium. In active MAP, additives are incorporated into the package that help to maintain or extend the product quality. Leak detection sensors (e.g., O_2, and CO_2) can thus monitor the condition of packaged food to give information about the fruit's quality. Reduced oxygen level in the packaging provides many benefits to fruits.

RFID-based sensor system.

Most of the previous sensing systems discussed focus on the quality of the fruits or fruit products, but there is still significant data that can be collected from the fruit container itself. Intelligent packaging can also make use of radio frequency identification device (RFID) technology to track and identify the product quality during storage and transport in containers. RFID tags are electronic barcodes used to identify individually packaged units whose data can be stored on a network and accessed later as needed. These systems require an RFID tag with an antenna, an RFID scanner, and utilize radio waves to communicate data to a network. The tag itself is an IC with an antenna, held together by a protective covering. When scanned, the RFID tag relays information about the package through the antenna to the reader, which has a receiver that transforms the radio waves emitted by the tag into the appropriate data format. These scanners can either be isolated units or can be connected to a central network that can store, processes, and further propagate the received data as designed.

Carbon dioxide non-dispersive infrared (NDIR) sensor.

Consumer packaging with modified atmospheric environment helps to ensure higher levels of carbon dioxide and low levels of oxygen within the package. Compromising the integrity of the package can lead to early decay in the fruit and the possibility of microbial infection. A high oxygen level accelerates the ripening of fruits as well as the growth of microbial organisms. In contrast, a low oxygen atmosphere slows down respiration and prevents the early ripening or fruit death. However, too low levels of oxygen can cause cell death leading to premature decay. Thus, the monitoring of atmospheric gases with a technique such as non-dispersive infrared (NDIR) sensors can help to ensure proper packaging conditions. A NDIR sensor uses infrared light absorption to determine the concentration of specific gases. Typically, light with wavelengths from 700 nm to 1 µm is shone through the air that contains the target gas to an optical detector. The atmospheric gases absorb certain wavelengths of light, while permitting others to pass through. Consequently, the amount of target gas particles that are present are measured by the amount of light absorbed, which is sensed by the optical detector that converts it into a measurable electrical output.

Challenges and Prospects

Current smart packaging technology has really set a solid foundational basis from which even more food-related processing can take place. While there is great potential for future applications, there are some challenges that may arise because of further development of this technology. The purpose of this section is to discuss some of these challenges and the prospects for food smart packaging.

Improvement of Sensor Technology- One of the main limiting factors for the further development of smart packaging is the limitation in sensory technology. While there are many sensors that could give accurate readings for different freshness parameters observed in produce and other food products, their usability, specifically size and cost, makes it difficult to incorporate them in large-scale packaged containers.

The balance between functionality, portability, and size has always been an area of interest in technology. This problem is even more pronounced in the food industry, as there is a push toward good quality foods with lower costs and high availability. One solution to this may be the further development of nanotechnology research in sensors. These sensors can be used to detect air emissions, temperature, humidity, and a variety of other environmental parameters. They also can perform more invasive measurements of food quality, without considerable damage to the product. While this type of technology is not yet economically viable for mass produced food packaging, with further research, it can be commercialized for highly accurate food quality sensing.

Temperature Cross-Sensitivity- Another important factor limiting the performance of freshness sensors is the effect of temperature cross-sensitivity. While some freshness sensors are intended to be temperature-sensitive and provide temperature-dependent freshness status of the fruit (e.g., time-temperature, microbial), some other sensors should not be affected by changes in temperature (e.g., electrochemical pH or ethylene sensors). Also, the activation energy or Q10-factor of a chemical process in any fruit should match with TTIs responses to provide accurate time–temperature profiles. Therefore, proper design considerations need to be taken when developing TTI and other sensors, which sometimes may require fruit-specific sensor design.

Improvement to Active Packaging Technology- One of the main motivations in improving food quality sensing is to be able to implement spoilage inhibitors through active packaging technology. An area of improvement in this research field is antimicrobial packaging. Food sanitization requires the removal of microbial organisms in order to prevent damage to the product. Current antimicrobial packaging systems generally use readily available inorganic compounds. The use of artificial chemical components in food processing is a possible safety concern, particularly in the case of unknown possible reactions or long-term effects. Therefore, these systems can be greatly improved by incorporating naturally derived bio-active agents.

Waste Management. Smart packaging consists of different technology embedded into one system. The monitoring systems and smart packaging systems, while necessary for food monitoring, pose problems for the disposal stage of the packaging. Most of the material used is neither biodegradable nor easily recyclable—indeed, some forms of packaging that utilize specific chemical compounds need to be carefully regulated during disposal. Research is currently being conducted in biodegradable or compostable materials for use in such technology, and while not all components can be completely replaced, those that can be substituted will significantly reduce the environmental impact of such systems.

Real-Time Control and Data Processing- The smart packaging technologies discussed in this review mainly involve self-contained sensor and active packaging technology that can perform on-site processing. New and novel smart packaging technology could potentially make use of the concept of the Internet of Things (IoT) to communicate with external processing units. IoT systems use networks to communicate and share data between multiple components of a system. IoT infrastructure expands on the idea of external communication that RFID systems offer by incorporating two-way data transmission between the "tag" and "reader" components. In this way, the package circuitry could be controlled by an external unit.

Conclusions

Current smart packaging systems along with embedded sensor and communication technologies can provide means of monitoring and regulating the quality of packaged fruits. Active packaging technologies extend these intelligent sensing systems by providing a mechanism to maintain food quality and mitigate any harmful environmental elements. Smart packaging technology can be used in a wide variety of food-related industries, including fresh produce. The nutritional value of fresh fruits and vegetables, along with its consumer popularity over frozen or canned alternatives, provides incentive for further development of quality sensing technology in this field. This technology can benefit the global food market by reducing the amount of preventable food spoilage that contributes to wasted resources. Specialized sensors can be used to detect observable characteristics of fruits and vegetables as they ripen and decay. By being able to monitor these features, actions can be taken to prolong the freshness and life span of perishable items in nonintrusive ways.

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Water Spinach: An Underutilized Super Crop for Food, Fodder and Health

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Water spinach (*Ipomoea aquatica* Forssk.), a member of the family Convolvulaceae, is a fast-growing herbaceous perennial leafy vegetable native to the tropical and subtropical regions of Asia (Gothberg *et al*., 2005). The crop thrives under aquatic, semi-aquatic, and moist upland conditions, where its long, hollow, trailing stems spread rapidly to form dense mats over water surfaces or wet soils. Adventitious roots emerge from the stem nodes, enabling efficient establishment under waterlogged conditions, while the leaves vary from sagittate (arrow-shaped) to lanceolate depending on the cultivar and growing environment.

Vernacular names

Water spinach is known by numerous vernacular names across Asia, reflecting its wide distribution and cultural significance. In English, it is commonly referred to as water spinach, water convolvulus, swamp cabbage, river spinach, and Chinese spinach. In Southeast Asia, it is popularly known as kangkong (Philippines and Malaysia), kang kung or rau muống (Vietnam), pak bung (Thailand), kong xin cai (Mandarin Chinese). In India, the crop is recognized by several regional names. It is known as Kalamba in Sanskrit, Kolmi Shak in West Bengal, Kolmou Xaak in Assam, Kalmi Saag in Bihar, Jharkhand and parts of Uttar Pradesh, Nari Soppu in Karnataka, Kalmi Bhaji in Maharashtra and Chhattisgarh, Kalmi Saag in Odisha (Austin, 2007).

Origin and distribution

Water spinach originated in India and is most commonly grown in East, South, and Southeast Asia (Van Wyk, 2005). It is used extensively in Indian, Burmese, Thai, Malay, Vietnamese, Filipino, and Chinese cuisines, especially in rural areas. In India, Water spinach is popularly grown in the eastern and northeastern states, particularly West Bengal, Assam, Odisha and Bihar, as well as in the southern states of Kerala, Tamil Nadu and Andhra Pradesh, where warm, humid conditions and abundant water resources favour its cultivation. In non-tropical areas, it is easily grown in containers given enough water in a bright sunny location (Enríquez, 2017; Dubey *et al*., 2019)

Medicinal and Health Benefits

Water spinach (*Ipomoea aquatica* Forssk.), commonly known as kangkong or swamp morning glory, is increasingly recognized as a functional food because of its exceptional nutritional composition and diverse health-promoting properties (Manvar & Desai, 2013). The tender shoots and leaves are rich in dietary fibre, high-quality protein, β-carotene, vitamins A, C and B-complex, essential minerals (iron, calcium, magnesium and potassium), and bioactive compounds such as flavonoids, carotenoids and phenolics. Its low caloric value (19 kcal per 100 g fresh weight) and high moisture content (>92%) make it an ideal vegetable for balanced diets, weight management and nutritional security (Igwenyi *et al*., 2011; USDA FoodData Central)

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Beyond its nutritional value, water spinach exhibits potent antioxidant, antimicrobial, anti-inflammatory and hepatoprotective activities, largely attributed to its rich phytochemical profile (Fu *et al*., 2011). Experimental studies have also demonstrated antidiabetic, anti-ulcer, neuroprotective and anticancer potential, highlighting its role in reducing oxidative stress and improving metabolic health (Ashraf *et al*., 2020). Traditionally, it has been widely used in Ayurvedic and Southeast Asian medicine for the management of anaemia, constipation, jaundice, liver disorders, fever, skin infections and gastrointestinal ailments. Fresh leaf juice has also been used for ulcers, general weakness and as an emetic in poisoning, while dried preparations possess mild purgative properties (DeFilipps & Krupnick, 2018). Although further clinical validation is needed, the available evidence supports the inclusion of water spinach as a nutrient-rich vegetable with significant potential for promoting human health and nutritional security.

Fig. 1. Water spinach growing in the experimental field at ICAR–Central Soil Salinity Research Institute (CSSRI), Karnal.

***Fig. 2.** General field view of the water spinach crop.*

Table. 1. Physio – Nutritional Composition of water spinach

Component	**Quantity (per 100 g fresh weight)**
Proximate Composition	
Water	92.47 g
Energy	19 kcal (80 kJ)
Protein	2.60 g
Total lipid (fat)	0.20 g
Ash	1.60 g
Carbohydrate	3.13 g
Dietary fibre	2.10 g
Minerals	
Calcium	77 mg
Iron	1.67 mg
Magnesium	71 mg
Phosphorus	39 mg
Potassium	312 mg
Sodium	113 mg
Zinc	0.18 mg

Copper	0.023 mg
Manganese	0.160 mg
Selenium	0.9 µg
Vitamins	
Vitamin C	55 mg
Thiamin (B1)	0.03 mg
Riboflavin (B2)	0.10 mg
Niacin (B3)	0.90 mg
Pantothenic acid (B5)	0.141 mg
Vitamin B6	0.096 mg
Folate (Total)	57 µg
Vitamin A (RAE)	315 µg
Vitamin A	6300 IU

(Source: USDA FoodData Central)

Uses

Culinary Uses and Agricultural Importance

Almost every tender part of the water spinach plant is edible; however, the young shoots and leaves are most preferred for their tenderness, pleasant taste, and superior nutritional quality. Water spinach is consumed in a variety of forms, including fresh salads, stir-fries, soups, curries, steamed dishes and noodle preparations. It occupies an important place in the traditional cuisines of Vietnam, Thailand, Cambodia, Myanmar, Malaysia, Indonesia, Philippines and southern China, where it is commonly prepared with garlic, chilli, soy sauce, oyster sauce or fermented fish paste (Austin, 2007; Dubey *et al*., 2019). In eastern and southern India, it is also cooked as stir-fries, coconut-based dishes, curries and mixed vegetable preparations, making it an inexpensive yet highly nutritious leafy vegetable. Beyond its culinary importance, water spinach has considerable significance in sustainable agriculture and climate-resilient food systems. The crop grows rapidly, regenerates quickly after repeated harvesting, and performs well under both wetland and upland conditions, allowing multiple harvests throughout the year. Because it requires comparatively low inputs, adapts to diverse environments and produces high biomass within a short duration, it is well suited for kitchen gardens, peri-urban farming, integrated farming systems and commercial vegetable production. Furthermore, its high nutritional density, adaptability to marginal lands and potential for year-round production make water spinach an attractive option for improving household nutrition, (FAO, 2018; Srivastava, 2022).

Water spinach as a green fodder and its potential

Water spinach (*Ipomoea aquatica* Forssk.) is an emerging high-quality green fodder owing to its rapid growth, high biomass production, excellent palatability, and superior nutritional value. The crop contains 18–34% crude protein (DM basis) with high digestibility, making it suitable for feeding cattle, buffaloes, goats, sheep, pigs, rabbits, ducks, and fish (Feedipedia, 2024). Feeding studies by Preston and co-workers demonstrated that water spinach significantly improved feed intake, nutrient digestibility, and animal growth, highlighting its potential as a cost-effective protein-rich forage (Chhay Ty & Preston, 2006. Recognizing its agronomic and nutritional potential, ICAR–Indian Institute of Vegetable Research (IIVR), Varanasi, developed 'Kashi Manu', India's first upland water spinach variety, characterized by rapid growth, repeated harvesting ability, high biomass yield, and adaptation to diverse agro-climatic conditions, making it a promising dual-purpose crop for integrated food–fodder systems and climate-resilient agriculture (Dubey *et al*., 2022; Waiba *et al*., 2025). However, biomass produced on heavy metal-

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contaminated sites should not be used as livestock feed.

Water spinach in phytoremediation

Water spinach (*Ipomoea aquatica* Forssk.) is increasingly recognized as an efficient phytoremediation species owing to its rapid growth, high biomass production, extensive fibrous root system, and exceptional capacity to accumulate and tolerate heavy metals. Numerous high-impact studies have demonstrated its ability to remove Cd, Pb, As, Cr, Cu, Zn, Ni, and Hg from contaminated soils, sediments, and wastewater through phytoextraction and rhizofiltration. For instance, Liu *et al.* (2009) reported exceptionally high Cd bioconcentration factors (375–2227 L kg^{-1} in roots), highlighting its superior Cd uptake efficiency. Studies by Zhang *et al.* (2021) and other researchers further demonstrated that water spinach effectively reduced heavy-metal concentrations in wastewater while maintaining substantial biomass production, making it suitable for constructed wetlands and wastewater treatment systems. More recently, integrated approaches combining water spinach with metal-resistant microorganisms or organic amendments significantly enhanced Cd and As removal while improving plant growth and reducing metal bioavailability. However, biomass harvested from contaminated sites should never be used for human consumption or livestock feeding because of the risk of heavy-metal transfer through the food chain.

Challenges and Future Prospects

Despite its immense potential, water spinach remains underutilized in India due to limited awareness, availability of improved varieties and organized cultivation. Since it can accumulate heavy metals, cultivation should be restricted to clean soils and irrigation water. Future efforts should focus on developing improved cultivars, strengthening seed systems and promoting its cultivation in climate-smart agriculture, hydroponics and integrated food–fodder systems. The development of 'Kashi Manu', India's first upland water spinach variety by ICAR–IIVR, marks a significant step towards its wider adoption (Dubey *et al.,* 2022; Waiba *et al*., 2025).

Conclusion

Water spinach is far more than a traditional leafy vegetable. Its exceptional nutritional value, medicinal potential, rapid growth, climate resilience and versatility as a vegetable, fodder and phytoremediation crop make it a promising species for sustainable agriculture. With increasing emphasis on food and nutritional security, climate-smart farming and environmental sustainability, wider cultivation, scientific validation and public awareness can transform water spinach into an important crop for the future, benefiting both farmers and consumers.

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AGRICULTURE BULLETIN

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Small bitter gourd (*Momordica charantia var. Muricata*): an underutilized vegetable with nutritional, medicinal and commercial potential

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Small Bitter Gourd (*Momordica charantia var. muricata*) is a small wild type bitter gourd. It is an under utilized vegetable with ethnobotanical and therapeutic values, under domestication interphase. Momordica charantia var. muricata, being a small fruited variant of the commercial large fruited bitter gourd, has been exploited less with respect to its biochemical and antioxidant properties. Small-fruited bitter gourds, In tamilnadu, it called as "Mithi paval" or "pavel" and "pandi-pavel" described in Hortus Malabaricus, is nearly an extinct crop in Kerala and rest of southern peninsular India. They are reported to have been cultivated extensively in the past. However, presently its cultivation is restricted to a few home gardens in remote forest areas consequent on its replacement by large-fruited cultivars over the last two centuries. Special traits like unique flavour, taste, medicinal properties and fruit fly tolerance have enabled the perpetuation of this relict vegetable still in a few homesteads.

Importance

1.Phytochemical and medicinal interest

Like other bitter gourd varieties, it's rich in bioactive compounds cucurbitane-type triterpenoids, charantin, momordicin, and various saponins — studied for antidiabetic, antimicrobial, and antioxidant properties.Wild varieties sometimes show higher concentrations of certain bioactive compounds than cultivated forms, making them attractive for pharmacological research.

2.Ecological role

Contributes to agrobiodiversity in the regions where it grows wild (parts of South/Southeast Asia, tropical Africa).Provides habitat and forage value in its native ecosystems.

3.Ethnobotanical use

In some regions, wild bitter gourd varieties are used in traditional/folk medicine and local cuisine, particularly where cultivated varieties aren't as accessible.

4.Conservation significance

As with many crop wild relatives, documenting and conserving var. muricata matters for maintaining the genetic base needed for future crop improvement, especially as climate change increases pressure on cultivated varieties.

Medicinal Importance

1. Antidiabetic activity

It contains charantin, polypeptide-p (a plant insulin analog), and vicine, which have shown blood glucose–lowering effects in animal and some human

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studies.Traditionally used across Asia, Africa, and the Caribbean as a folk remedy for diabetes management.Wild varieties like var. muricata sometimes show higher concentrations of these compounds than cultivated forms, making them a focus of comparative phytochemical studies.

2. Antimicrobial and antiparasitic properties

Extracts have demonstrated activity against various bacteria, fungi, and some parasites in lab studies. Momordicin and other triterpenoids are thought to contribute to this effect.

3. Antioxidant activity

Rich in phenolic compounds and flavonoids that scavenge free radicals, which is why it's studied in the context of oxidative stress–related conditions.

4. Anticancer research (preliminary)

Some in vitro and animal studies suggest cucurbitane triterpenoids from Momordica species may inhibit growth of certain cancer cell lines, but this research is early-stage and far from clinical application.

5. Anti-inflammatory and hepatoprotective effects

Traditional use includes treatment of liver ailments and inflammatory conditions; some animal studies support protective effects on liver tissue.

(FACT: "Muricata" literally refers to its rough, spiny (muricate) fruit surface — so its whole name is a nod to its prickly look).

Origin And Distribution

Small bitter gourd *(Momordica charantia var. muricata)* is believed to have originated in the Indo-Malayan region and is widely distributed throughout tropical and subtropical Asia. It occurs naturally in India, Sri Lanka, Bangladesh, Myanmar, Thailand, Malaysia, Indonesia and parts of tropical Africa. In India, it is mainly found in Tamil Nadu, Kerala, Karnataka, Andhra Pradesh and the North-Eastern states. Traditionally, it was cultivated in home gardens and forest fringes, but its cultivation has declined due to the popularity of commercial large-fruited bitter gourd cultivars.

Nutritional Composition

Nutrient

Amount (per 100 g fresh fruit)

Moisture 90–92 g

Energy 17–22 kcal

Protein 1.0–1.5 g

Carbohydrates 3.5–4.5 g

Dietary fibre 2–3 g

Calcium 20–30 mg

Iron 0.5–1.2 mg

Phosphorus 30–40 mg

Potassium 250–300 mg

Vitamin C 80–100 mg

β-carotene 120–180 µg

Taxonamical Classification

Kingdom: Plantae

Division: Magnoliophyta

Class: Magnoliopsida

Order: Cucurbitales

Family: Cucurbitaceae

Genus: Momordica

Species: *Momordica charantia L.*

Variety: *M. charantia var. muricata (Willd.)*

Botony

Annual climber with unbranched glabrous tendrils, monoecious. Stem pubescent to glabrescent. Leaves orbicular, 1.5-5.0 (-12.0) cm long and as broad, cordate, glabrous or sparsely hairy, 3-5-lobed, middle lobes broadly ovate or rhombic-ovate, sinuate-dentate or acutely lobulate.

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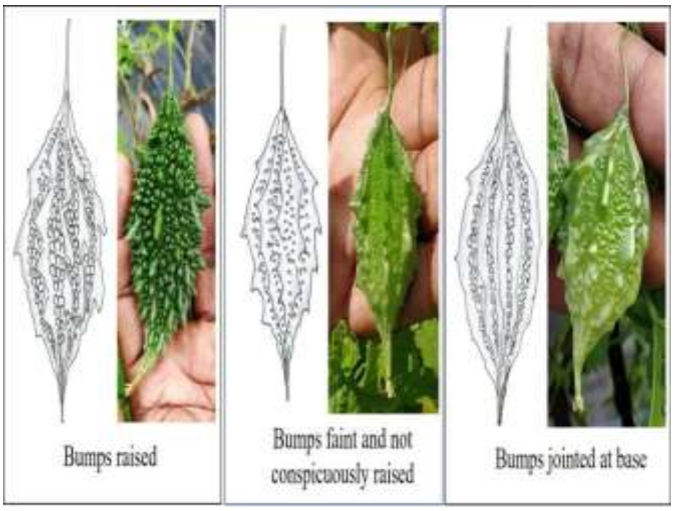
Petiole 1-3(-4) cm long, pubescent. Flowers yellow, 2.5-3.0 cm across, pedicellate. Male flowers solitary, on 1.5(-7) cm long peduncle, bearing near the apex a sessile, broadly ovate-cordate, subglabrous, dentate bract.

female flowers on 5-15 mm long basally bracteate or ebracteate peduncles. Calyx tube 5-6 mm long, pubescent, lobes ovate, acuminate, 3-3.5 mm broad. Corolla slightly zygomorphic, brown at base, lobes yellow, obovate, 10-15 mm long, 8-10(-12) mm broad. Ovary fusiform, beaked, longitudinally tuberculate.

Fruit broadly ovoid, narrowed at ends, 2-7 cm long, 1-2.5 cm broad, orange-red, tuberculate. Seeds elliptic-ovate, 1-1.2 cm long, 6-7 mm broad.



ISSN: 3049-2289

Cultivation Aspects Of Small Fruited Bitter Gourd

Climate & soil:

Thrives in warm, tropical, and subtropical conditions with plenty of direct sunlight, adapting efficiently to low-input or zero-budget natural farming systems.

Sowing Time:

Kharif Season: Sowing takes place between June and July.

Rabi Season: Sowing occurs between December and January.

Perennial Schedule: Under warm, frost-free climates with stable irrigation, seeds can be successfully sown from January to December.

Spacing Requirements:

Because var. muricata has a spreading, creeping habit rather than a tall climbing form, it requires distinct layout designs:

Sowing Method:

Seed Preparation: Soak the hard-coated seeds overnight in cold water for 24 hours to improve early germination.

Direct Dibbling: Plant 4 to 5 seeds per pit directly into moist field basins at a depth of 2.0 to 3.0 cm.

Seedling Nursery (Optional): For uniform field stands, raise seedlings in 200-gauge polybags (10 cm × 10 cm) for 15 days before transplanting.

Thinning: Over the first 15 days post-emergence, thin the weaker sprouts to leave exactly 2 healthy seedlings per pit.

Fertilizer Application:

Nutrient application should combine organic manures with targeted mineral doses

Basal Manuring: Mix 10 kg of well-decomposed Farm Yard Manure (FYM) into each pit (equivalent to approximately 20 tonnes per hectare) prior to sowing.

Biofertilizers: Integrate 2 kg/ha each of Azospirillum and Phosphobacteria into the soil before final tillage.

Basal Chemical Dose: Apply 100 grams of NPK 6:12:12 compound fertilizer per pit along with the basal organic manure.

Top Dressing: Side-dress with 10 grams of straight Nitrogen per pit (roughly 22 grams of Urea) 30 days after sowing to drive vine extension.

Crop Duration: The total crop lifecycle from planting to final harvest spans approximately 120 days.

Yield Potential: Yields average around 2,000 to 2,150 kg per hectare under standard evaluation trials, producing a high number of small, tuberculate fruits (individual fruit weights range from 2.5g to 7.5g) rich in medicinal properties, calcium, iron, and vitamin C.

Cold Storage & Shelf life Management

Optimal Temperature: Store the packed baby bitter gourds at 10°C to 12.5°C under 85% to 90% relative humidity. This configuration successfully extends fresh shelf life up to 14 days.

Chilling Injury Warning: Do not store the fruits below 7.5°C. Temperatures this low cause chilling injuries, manifesting as severe pitting, watery decay, and rapid browning.

Ambient Alternative: If refrigeration is unavailable, cover the bulk storage crates with a clean, wet gunny cloth. Alternatively, utilize a low-cost evaporative village cooling chamber to preserve moisture and slow down softening.

ISSN: 3049-2289

Secondary Processing & Value Addition

Given its high concentration of therapeutic compounds, Momordica charantia var. muricata is heavily utilized for processed medicinal products rather than just fresh culinary use:

1. Solar or Mechanical Dehydration

Slices of the whole baby bitter gourd are pre-treated with a salt brine solution to retain their green coloration. The slices undergo hot air cabinet drying at 55°C to 60°C until moisture levels drop below 6%. The dehydrated slices are either sold directly for herbal teas or milled into antidiabetic bitter gourd powder.

2. Juices and Blended Extract Nectars Freshly extracted juice is highly prone to oxidation and enzymatic browning. To stabilize the extract and soften the extreme bitterness, processors mix the juice with high-carotenoid papaya pulp and vitamin C-rich aonla (Indian gooseberry) juice at an optimized ratio of 50:25:25. This results in a stable functional beverage requiring no synthetic preservatives.

3. Solvent Extraction for Pharmaceuticals Dried fruit tissue is subjected to ethanolic or methanolic extraction workflows. Ethanol is preferentially utilized to efficiently extract essential macrominerals like calcium and magnesium, while methanol maximizes the yields of isolated charantin and antioxidant fractions.

Value Added Products

Common value-added products made from small bitter gourd include dried slices, powders, and juices. These items help reduce waste and make the vegetable easier to use.

Processed Food and Snack Products

Chips and Crisps: Thin slices fried or baked with spices to make a crunchy snack.

Dried Rings: Sun-dried or dehydrated gourd pieces used later for frying or cooking.

Pickles: Tangy and spicy oil- or brine-based preserves that cut the sharp bitter flavor.

Health and Herbal Products Karela Powder: Ground dried fruit used In herbal mixes and capsules to help manage blood sugar.

Juice Extracts: Bottled or blended pure juice used as a natural wellness tonic.

Instant Soup Mixes: Dried vegetable flakes added to health soups and instant meal packets.

constraints in cultivation

- Low farmer awareness.
- Limited availability of quality seeds.
- Lack of improved varieties.
- Low market demand compared with large bitter gourd.
- Insufficient research.
- Poor post-harvest management.
- Short shelf life.

Conclusion

Small bitter gourd *(Momordica charantia var. muricata)* is an underutilized indigenous vegetable crop possessing remarkable nutritional, medicinal, and genetic importance. The crop is rich in bioactive compounds such as charantin, momordicin, phenolics, and flavonoids, which contribute to its antioxidant, antidiabetic, antimicrobial, and anti-inflammatory properties. Besides its therapeutic potential, the species serves as a valuable genetic resource for the improvement of cultivated bitter gourd because of its tolerance to fruit fly infestation and adaptability to diverse environmental conditions. Despite these advantages, its cultivation has declined due to the replacement of traditional landraces by commercial cultivars. Therefore, conservation, scientific cultivation, and value addition are essential to preserve this unique crop and enhance its commercial utilization. Promoting awareness among farmers, researchers, and consumers can contribute significantly to the sustainable utilization of this valuable vegetable.

Future Aspects

Future research on Momordica charantia var. muricata should focus on the conservation of indigenous germplasm, genetic improvement, and the development of high-yielding cultivars with enhanced nutritional and medicinal qualities. Advanced breeding techniques, molecular characterization, and genome-assisted selection can be employed to improve fruit quality, yield, and resistance to pests and diseases. Further studies are needed to validate its pharmacological properties through clinical investigations and to identify novel bioactive compounds for pharmaceutical applications. Standardization of cultivation practices, postharvest handling, and processing technologies will improve productivity and shelf life. Additionally, the development of functional foods, nutraceuticals, herbal formulations, and value-added products can increase market demand and farmer income. With increasing consumer preference for natural health-promoting foods, small bitter gourd has considerable potential to become an important crop in sustainable agriculture and the nutraceutical industry.

Recent Research Advances (2020–2026)

Recent studies have identified cucurbitane-type triterpenoids, charantin, momordicosides, flavonoids, and phenolic compounds as the major bioactive constituents responsible for antioxidant, antidiabetic, anti-inflammatory, and antimicrobial activities.

Advanced extraction techniques such as ultrasound-assisted extraction, microwave-assisted extraction, and supercritical fluid extraction improve the recovery of bioactive compounds compared with conventional methods.

Molecular studies indicate that Momordica charantia extracts regulate glucose metabolism through AMPK activation, enhanced insulin sensitivity, and antioxidant pathways, supporting its use as a functional food.

Current evidence supports strong antioxidant, antimicrobial, hepatoprotective, and anti-inflammatory activities, but researchers emphasize that well-designed human clinical trials are still needed before many therapeutic claims can be confirmed.

Recent reviews also highlight the potential of bitter gourd for nutraceuticals, functional foods, pharmaceutical formulations, and value-added products, making it an economically important crop for future commercialization.

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Role of Azolla in sustainable agriculture

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Sustainable farming practices aim to balance food production with environmental conservation through strategies that include minimizing chemical use, managing water effectively, and restoring ecosystems while reducing green house gas emissions. Rapid population growth, climate change, and natural resource depletion create an urgent global challenge for agricultural sustainability.

Among various alternatives, Azolla, a fast-growing aquatic fern, has gained significant attention for its unique biological properties and potential role in sustainable agriculture and climate resilience. This aquatic fern forms a symbiotic relationship with Anabaena azollae to fix atmospheric nitrogen, enabling it to function as a biofertilizer that reduces synthetic fertilizer use while preventing soil acidification and nitrous oxide emissions. Azolla contributes to rapid biomass generation, carbon sequestration, and methane reduction. Azolla also purifies water by absorbing heavy metals and pollutants, while serving as a high-protein livestock and aquaculture feedstock (25–33% crude protein), making it both a sustainable and economical supplement. The primary focus is on Azolla's role in rice and crop-based systems, while livestock and aquaculture are discussed as complementary but integral components of agricultural systems.

Role of Azolla in sustainable agriculture:

Azolla has long been used in agriculture mostly for water conservation, weed control, and soil fertility enhancement. Its use as a biofertilizer in rice systems, when farmers applied it as green manure to boost rice yields. The symbiotic relationship between Azolla and A. azollae enables Azolla to function as a natural source of nitrogen through direct atmospheric nitrogen fixation into the plant. In flooded rice systems, fixation rates of 2–4 kg N per hectare per day have been reported, substantially reducing the need for synthetic fertilizers and positioning Azolla as an important component of sustainable agriculture. This biologically sourced nitrogen not only lowers production costs but also minimizes environmental contamination compared to chemical fertilizers.

In rice paddies, the dense floating mat of Azolla suppresses weeds by blocking sunlight and reduces water loss through evaporation, thereby decreasing reliance on herbicides and manual weeding. Azolla has long been used as livestock and aquaculture feed due to its protein-rich composition and balanced amino acid profile. More recently, it has been adopted in Iran, Africa, and parts of Europe for rice cultivation and aquatic farming.

Azolla application in rice cultivation:

Azolla significantly enhances rice grain yield, straw yield, caryopsis formation, and dry matter production when incorporated into paddy fields. It is applied either as green manure before transplanting or as a dual crop after transplanting, with the latter being more widely adopted due to its greater agronomic benefits. In the green manure system, Azolla is collected from nurseries, ponds, or ditches and applied 2–3 weeks before rice transplanting. The process begins by spreading inoculums at 0.5 kg m^{-2}. After one week, when the surface is fully covered, half of the Azolla is transferred to a new area of equal size. Within another week, both areas will reach full coverage. This cycle is repeated, doubling the covered area each time, leading to exponential expansion.

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Azolla forms a thick mat that decomposes into the soil, supplying 20–40 kg N/ha and enhancing soil fertility and crop yields. In dual cropping systems, introducing 0.5–1 t/ha of fresh Azolla after transplanting allows a dense mat to form within 15–20 days. Decomposing in 8–10 days, it releases nitrogen to support rice growth throughout the crop cycle, providing approximately 30 kg N/ha per cycle. To optimize nitrogen fixation, superphosphate (20kg/ha) is applied in split doses.

Azolla in water conservation, weed, and pest control:

The thick Azolla mat prevents sunlight from reaching submerged weed seeds, inhibiting germination and growth. This eco-friendly method provides an alternative to herbicides. Previous studies show that Azolla can reduce weed biomass by up to 50%. Since weeds compete with rice for nutrients, light, and water, infestations can cause yield losses of 16–100% depending on severity. Unlike herbicides such as 2,4-D, glyphosate, and propanil, which harm non-target organisms and degrade soil and water quality, Azolla offers a safer alternative. Azolla effectively suppresses multiple weeds, including Echinochloa crus-galli, Cyperus serotinus, Monochoria vaginalis, Eclipta prostrata, Fimbristylis miliacea, and Cyperus rotundus. By blocking light, altering microclimate (reducing evaporation and soil temperature), and improving soil structure when incorporated as green manure, Azolla reduces weed competition and enhances rice growth.

The floating Azolla mat also disrupts pest life cycles. It prevents mosquitoes from laying eggs on water surfaces, lowering mosquito populations and reducing vector-borne disease risk. It interferes with the breeding of rice stem borers and leafhoppers, which require open water for egg-laying. Furthermore, Azolla supports beneficial organisms such as predatory insects, frogs, and fish, which feed on pest larvae, thereby enhancing natural pest control mechanisms and reducing the need for chemical pesticides. In integrated rice–fish systems, Azolla not only acts as biofertilizer and fish feed but also suppresses weeds and pests, reducing chemical inputs and maintaining ecological balance.

Azolla as animal feed:

Azolla is a nutrient-rich, high-protein feed supplement for livestock, poultry, and fish. It provides an excellent amino acid profile, high digestibility, and essential micronutrients, serving as a sustainable alternative to conventional protein feeds such as soybean meal and fish meal, which are costly and environmentally intensive. Azolla is also rich in lysine, methionine, and arginine, essential for muscle growth, as well as key minerals like calcium, phosphorus, magnesium, iron, and potassium, which support bone health and metabolism. High beta-carotene and vitamin A levels enhance vision, immunity, and reproduction. Its low lignin content (<5%) ensures high digestibility for both ruminants and nonruminants. while bioactive compounds such as flavonoids and phenolics improve gut health, feed efficiency, and disease resistance.

Azolla in dairy and meat production:

Azolla supplementation in dairy cattle diets improves milk yield, enhances milk quality, and reduces feed costs. Replacing 15–25% of commercial feed with Azolla in crossbred cows increased milk and fat percentage and yield by 7–13%, while reducing feed costs by 20–25%. A 10–15% replacement of conventional cattle feed increased milk yield by 15–20%, with improved fat and protein content. Fresh supplementation of up to 1 kg/day increased yield by 7–13%, with extended feeding (28–63 days) further enhancing production. In buffaloes, daily feeding of 1.5 kg Azolla increased milk yield by 15–20%, while supplementation with cottonseed cake raised output from 8.0 to 9.3 L/day. In beef cattle and meat production, feeding Azolla to cattle and goats for two months increased milk production by 10–15% and meat yield by 8–10%. Feeding 5% dried Azolla improved feed conversion efficiency by 20% and daily gain by ~16% in heifers. The substitution of groundnut cake nitrogen with Azolla in buffalo calves improved daily weight gain, while 25% protein replacement in Murrah bulls' concentrate had no negative effect.

Azolla as poultry feed:

Azolla is a sustainable poultry feed rich in protein, essential amino acids, vitamins, and bioactive compounds, enhancing growth performance and feed efficiency. A 5% Azolla inclusion enhanced broiler weight gain and feed efficiency, while 10% increased weight gain and reduced feed intake. A 7.5% inclusion improved body weight by 2.6%, with optimal growth at 5–10%. Azolla supports digestion and gut microbiota in poultry, enhancing digestibility at 10–15% inclusion. Broilers fed 10% Azolla gained 1810 g versus 1270 g on conventional feed, with improved digestibility linked to increased duodenal thickness. A 5–7% Azolla diet with multivitamins and acidifiers lowered feed conversion ratio, mortality, and costs while boosting profit.

Previous studies reported that the Azolla fiber was more digestible than rice bran and supported metabolism, immunity, and gut health in chickens and safety was confirmed up to 7% inclusion. Azolla supplementation (5–10%) boosted immunity, likely due to its carotenoids, minerals, and nitrogen-fixing Anabaena. Previous studies confirmed that Azolla enhances egg production and quality without adverse effects up to 20% inclusion. Layers fed 100 g/day produced more eggs at lower costs. Ducks on a 10–20% Azolla diet showed increased egg weight and better feed conversion. A 5% inclusion improved egg production (53.2 vs. 49.9 on concentrate, 47 on forage) and body weight. Fresh Azolla supported growth in backyard poultry, while its carotenoids enhanced yolk pigmentation and egg yield.

Additionally, Azolla enhances meat quality and overall health outcomes in poultry. For example, a 5% Azolla diet significantly increased dressing percentage, while a 4.5% diet improved giblet yield and reduced serum cholesterol. Broilers fed 5–10% Azolla exhibited better meat color and reduced cooking loss. However, excessive supplementation may cause a greenish tint in meat.

Azolla in aquaculture and fish farming:

Azolla has been extensively investigated as a potential feed supplement in aquaculture due to its high protein content, balanced amino acid profile, and natural pigments, which contribute to improved growth rates and enhanced coloration in fish species.

Additionally, the incorporation of Azolla in fish diets has been shown to enhance water quality by absorbing excess nutrients and mitigating algal blooms, thereby creating a more balanced aquatic environment. Various freshwater fish species have been successfully fed Azolla-based diets in controlled experimental settings.

Azolla supplementation also boosts goblet cell production, strengthening the mucosal barrier and enhancing disease resistance in fish.

Other uses of Azolla:

Azolla is a promising and sustainable biofuel feedstock due to its rapid growth, high lipid content, and adaptability to various conversion processes. Pyrolysis of Azolla yields hydrocarbons, including straightchain alkanes, making it a potential diesel substitute. However, its high moisture content requires drying, and heavy metal emissions must be managed. Activated carbon catalysts improve both bio-oil yield and quality. Transesterification is another widely studied method for biodiesel production. Crude oil extracted from dried Azolla biomass can be processed through acid transesterification to produce fatty acid methyl esters with properties like conventional diesel. Efficiency depends on maintaining optimal reaction temperatures (47–60°C) and reactant ratios, which require further study.

Azolla is also a promising feedstock for bioplastics due to its rapid growth, high biomass yield, and diverse biochemical composition.

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Conclusion:

Azolla is a multifunctional resource that supports sustainable agriculture and climate resilience. Its symbiosis with A. *azollae* enables efficient nitrogen fixation, reducing dependence on synthetic fertilizers while enhancing soil health, conserving water, and suppressing weeds and pests. As a high-protein feed, Azolla improves livestock, poultry, and aquaculture performance, though anti-nutritional factors and compositional variability remain challenges.

Beyond agriculture, Azolla contributes to climate change mitigation through rapid carbon sequestration and reduced methane emissions in rice systems, while also offering bioremediation potential for polluted waters. Its emerging applications as a feedstock for biofuels and bioplastics further highlight its industrial value.

Overall, Azolla represents a low-cost, eco-friendly tool with wide-ranging benefits across food production, climate mitigation, and environmental management.

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Soil Degradation in India: Scenario, Status, Symptoms and Pathways to Sustainable Management

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Soil forms the fundamental base of terrestrial life, supporting nearly 95 per cent of global food production while regulating water cycles, storing carbon and sustaining biodiversity. In India, an agrarian economy, progressive soil degradation driven by water and wind erosion, nutrient imbalance, declining organic carbon, salinization, intensive cultivation and climate extremes poses a serious threat to food security and environmental stability. Approximately 30 per cent of the country's geographical area (about 97 million hectares) is estimated to be affected by land degradation. Water-induced erosion accounts for nearly 68 per cent of total soil loss. Visible symptoms include topsoil depletion, reduced crop yields, increased frequency of floods and droughts, gully formation, sedimentation of water bodies and loss of soil biodiversity. This article examines the current scenario and status of soil health in India, identifies key symptoms and drivers of degradation, and outlines integrated sustainable solutions encompassing conservation agriculture, watershed management, agroforestry, soil-health improvement measures, climate-resilient practices and community participation. Strengthening ongoing government programmes such as the Soil Health Card Scheme, PMKSY and NMSA, coupled with digital monitoring tools, is essential for restoring soil productivity and securing long-term agricultural sustainability.

Introduction

Soil is far more than a medium for plant growth; it is a living, dynamic natural resource that underpins food systems, regulates hydrological processes, sequesters atmospheric carbon and maintains the biological diversity of terrestrial ecosystems. Globally, healthy soils support the production of the vast majority of food consumed by humans. Yet this critical resource is under mounting pressure. Unsustainable land-use practices, intensive agriculture, deforestation, mining, urban expansion and the growing influence of climate change are accelerating the rate of soil degradation worldwide.

India, with its predominantly agrarian economy and dense rural population, is particularly vulnerable. Fertile alluvial plains, productive black soils and diverse agro-ecological zones have historically sustained high levels of agricultural output. However, decades of intensive cultivation, imbalanced fertiliser use, declining organic matter, over-extraction of groundwater and extreme weather events have progressively undermined soil quality across large parts of the country. The loss of productive topsoil not only reduces crop yields but also diminishes the

capacity of landscapes to buffer floods, recharge aquifers and support biodiversity. Restoring and protecting soil health has therefore become an urgent national priority linked directly to food security, climate resilience and sustainable development goals.

ISSN: 3049-2289

2. Global and National Scenario of Soil Degradation

International assessments indicate that nearly one-third of the world's soils are moderately to highly degraded. Climate variability, characterised by intense rainfall events interspersed with prolonged dry spells, together with continued expansion of intensive farming systems, continues to drive erosion and fertility decline on a global scale.

In the Indian context, water and wind remain the principal agents of soil erosion. Studies, including research associated with the Indian Institute of Technology Delhi, suggest that rainfall and surface runoff account for approximately 68 per cent of total soil erosion, establishing water as the dominant erosive force. The problem is especially acute in flood-prone plains, steep Himalayan and north-eastern hill slopes, and semi-arid regions of western and central India. States such as Rajasthan, Maharashtra, Odisha, Gujarat, Assam, Meghalaya, Jharkhand, Bihar and Uttarakhand report significant erosion-related land degradation, with consequent declines in agricultural productivity and heightened environmental vulnerability.

3. Current Status of Soil Health in India

Recent estimates suggest that during 2025–26 nearly 30 per cent of India's geographical area equivalent to roughly 97 million hectares is affected by various forms of land degradation and soil erosion. The fertile topsoil layer, rich in organic matter and plant nutrients, is being lost at an alarming rate through the combined action of heavy monsoon rains, floods, wind, deforestation and inadequate land management.

India possesses a wide range of soil types alluvial, black (vertisols), red, laterite, desert, forest and mountain soils each with distinct characteristics and management requirements. While many regions continue to support high agricultural productivity, a growing number of areas exhibit clear signs of deterioration: declining soil organic carbon, nutrient imbalances (particularly secondary and micronutrient deficiencies), rising salinity and sodicity in irrigated tracts, soil acidity in high-rainfall zones, and physical degradation through compaction and crusting.

On a positive note, advances in remote sensing, Geographic Information Systems (GIS), digital soil mapping and artificial intelligence are enabling more precise identification of degradation hotspots and better targeting of interventions. Parallel government programmes are expanding the reach of scientific soil management practices across the country.

4. Symptoms of Soil Degradation

Healthy soil is characterized by good physical structure, adequate moisture-holding capacity, balanced nutrient status and a rich community of soil organisms. When degradation sets in, several diagnostic symptoms become evident:

- Progressive loss of fertile topsoil through sheet, rill and gully erosion by water or through wind action.
- Declining levels of soil organic carbon and reduced availability of both macro- and micronutrients.
- Stagnation or decline in crop yields and farm income despite continued or increased input use.
- Increased incidence and severity of floods, droughts and landslides in affected landscapes.
- Formation of gullies, ravines and permanently barren patches.

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- Accelerated sedimentation of rivers, reservoirs, ponds and irrigation canals, reducing their storage and conveyance capacity.
- Impaired groundwater recharge and declining water-table levels.
- Reduction in soil biological activity and diversity of beneficial microorganisms.
- Development or intensification of soil salinity, sodicity, acidity or compaction.
- Greater susceptibility of crops to climatic stresses, pests and diseases.

These symptoms collectively demonstrate that soil degradation is not merely an agronomic problem; it is a multi-dimensional environmental and socio-economic challenge.

5. Major Drivers of Soil Degradation

Both natural processes and anthropogenic activities contribute to the observed decline in soil quality:

- High-intensity rainfall and unchecked surface runoff, especially on sloping lands.
- Strong winds in arid and semi-arid zones leading to aeolian erosion.
- Deforestation, forest degradation and recurrent forest fires.
- Unsustainable agricultural practices, including excessive tillage, monocropping and residue removal.
- Overgrazing of pasture and common lands.
- Mining, quarrying and large-scale infrastructure development.
- Rapid urbanisation and conversion of agricultural land.
- Inappropriate irrigation practices resulting in waterlogging and secondary salinization.
- Climate change, which amplifies the frequency and intensity of extreme weather events.

6. Sustainable Solutions for Soil Conservation and Restoration

Arresting and reversing soil degradation requires a multi-pronged strategy that integrates scientific knowledge, ecological principles and active community involvement.

6.1 Sustainable Agricultural Practices

Adoption of conservation agriculture (minimum or zero tillage, permanent soil cover and crop diversification), integrated nutrient management, organic farming, green manuring and balanced fertiliser application based on soil-test recommendations can simultaneously improve soil structure, organic carbon stocks and nutrient-use efficiency.

6.2 Afforestation and Agroforestry

Increasing vegetative cover through tree planting, shelterbelts, contour plantations and well-designed agroforestry systems reduces the erosive impact of rain and wind, enhances biodiversity and provides additional income streams to farming households.

6.3 Watershed and Water Management

Construction of check dams, contour bunds, graded bunds, farm ponds, percolation tanks and other rainwater-harvesting structures slows runoff, promotes infiltration and reduces sediment loss. Integrated watershed development remains one of the most effective landscape-scale approaches to soil and water conservation.

6.4 Soil Health Improvement Measures

Regular soil testing under the Soil Health Card programme, widespread use of compost, vermicompost, biofertilisers and crop residues, and correction of micronutrient deficiencies are essential for restoring the biological and chemical fertility of soils.

6.5 Climate-Resilient Land Management

Promotion of climate-smart agricultural practices including drought- and flood-tolerant varieties,

ISSN: 3049-2289

efficient irrigation (drip and sprinkler systems), residue mulching and diversified cropping systems enhances the adaptive capacity of farming systems to climatic extremes.

6.6 Scientific Monitoring and Digital Tools

Continued investment in satellite-based monitoring, drone surveys, GIS-based decision-support systems and digital soil maps enables real-time assessment of erosion risk and more precise allocation of conservation resources.

6.7 Community Participation and Capacity Building

Long-term success depends on the active engagement of farmers, local institutions, educational organisations and civil-society groups. Awareness campaigns, farmer field schools and participatory planning processes are indispensable for scaling up sustainable land management.

7. Key Government Initiatives

The Government of India has put in place a comprehensive policy and programmatic framework to address soil degradation and promote sustainable agriculture. Important ongoing initiatives include:

- Soil Health Card Scheme – providing farmers with soil-test-based nutrient recommendations.
- Pradhan Mantri Krishi Sinchayee Yojana (PMKSY) – expanding irrigation coverage and improving water-use efficiency.
- National Mission for Sustainable Agriculture (NMSA) – promoting climate-resilient and resource-efficient farming systems.
- Integrated Watershed Management Programme and subsequent watershed development schemes.
- Afforestation and Green India Mission activities.
- Riverbank stabilisation and flood-control projects.
- Promotion of organic and natural farming practices.
- Digital soil mapping and erosion-risk assessment programmes.

Collectively, these programmes aim to enhance soil fertility, conserve natural resources, raise agricultural productivity and support sustainable rural livelihoods.

8. Conclusion

The evidence on the scenario, status and symptoms of soil degradation in India leaves little room for complacency. Productive soils are being lost at a rate that threatens long-term food security, water security, biodiversity and climate resilience. Soil degradation is no longer a purely agricultural issue; it is a central challenge for environmental sustainability and rural prosperity.

Reversing this trend demands coordinated action by governments, research institutions, extension systems, farmers and civil society. Scaling up proven practices conservation agriculture, watershed management, agroforestry, balanced nutrition, digital monitoring and community-based approaches offers a practical pathway toward restoring degraded lands. Protecting and regenerating India's soils today is an investment in the food, water and environmental security of future generations. The time for decisive, collective action is now.

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Invite the Birds, Protect the Crop: Nature's Pest Control Partners

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Birds are often perceived as crop pests because some species feed on standing crops, particularly rice, millets, sunflower, fruits and other agricultural produce. When farmers observe birds feeding on grains or fruits, it is easy to assume that all birds visiting a field are harmful. However, this is not the case. Many birds found in agricultural landscapes are natural allies of farmers and can contribute to the regulation of insect pests and other agricultural pests. A global meta-analysis of studies from agricultural and forest systems found an overall positive effect of avian regulation on pest-related indicators, including pest abundance, crop damage and yield (Monteagudo et al., 2023).

Species such as the Black Drongo, Common Myna and various insectivorous birds feed on caterpillars, moths, grasshoppers, beetles and other insects that attack crops. Similarly, owls are important nocturnal predators of rats and mice in agricultural fields. Encouraging these natural predators can therefore form an important component of ecological pest management. Managing agricultural landscapes as living ecosystems, rather than simply as crop-production areas, can help balance crop production with biodiversity conservation and ecosystem-based management (Manikandan et al., 2026).

However, simply having beneficial birds in and around a farm is not always sufficient. Birds need suitable places from which they can rest, observe the field, locate prey and launch attacks. Traditionally, trees, shrubs, fence posts and dry branches along field bunds provided such natural perching sites. With the expansion of large mono cropping fields, these natural perches are increasingly disappearing. As a result, beneficial birds may have fewer opportunities to remain in the field and hunt insect pests.

A simple way to compensate for this loss of natural perching sites is to install bird perches. These structures provide elevated observation points from which birds can monitor crop fields and hunt insect pests. Stronger and taller perches can also provide suitable hunting platforms for owls, helping to promote natural rodent management.

What is Bird Perch?

A bird perch is a simple artificial structure installed in a crop field to provide birds with a suitable elevated place for resting, observing and hunting. Bird perches are commonly made from locally available materials such as bamboo poles, dry wooden branches or other sturdy materials. A simple T-shaped perch is one of the most commonly used designs. It functions like a small "observation tower", allowing birds to obtain a clear view of the crop.

Why are Bird Perches Important?

Many insectivorous birds, including drongos and mynas, do not continuously fly around the field looking for prey. Instead, they often use a "sit-and-wait" hunting strategy. They sit on an elevated point, observe the surrounding area and quickly fly down or forward when prey is detected.

In a crop field without suitable perching sites, birds may have to spend more energy searching for prey and may not remain in the field for long periods. Providing bird perches offers several advantages:

- Birds obtain a convenient place to rest and observe the crop.
- They can detect moving insects more easily from an elevated position.
- Energy expenditure associated with continuous flight is reduced.
- Birds can repeatedly hunt insects within the same field.
- The presence and activity of natural predators can be encouraged.

Bird perches can therefore be viewed as a simple conservation biological control intervention that supports naturally occurring predators and complements Integrated Pest Management (IPM). Habitat-based approaches that protect and enhance natural enemies are an important component of conservation biological control (Ayyamperumal et al., 2020).

The Science Behind Bird Perches

A bird perch is more than simply placing a stick in a field. It is a management practice designed around the natural hunting behaviour of birds.

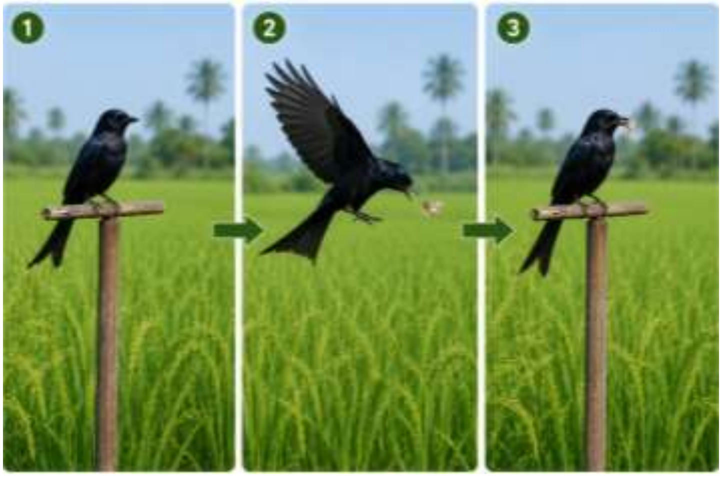
1. Better Observation from an Elevated Position

When a bird sits above the crop canopy, it can observe a larger portion of the field. Moving caterpillars, leafhoppers, grasshoppers, moths and other insects can be detected more easily from an elevated position.

2. Energy Conservation

Searching continuously for prey while flying requires considerable energy. By sitting on a perch and waiting for prey to appear, birds can hunt more efficiently while using less energy.

3. “Swoop, Capture and Return” Behaviour



Once prey is detected, the bird can quickly fly down or forward from the perch, capture the insect and return to the perch. It can then consume the prey and continue waiting for the next opportunity.

This behaviour allows a single bird to potentially capture several insect pests while remaining within the same field.

Providing artificial perching sites is also consistent with the principle of ecological engineering, in which the farm environment is deliberately modified to favour beneficial organisms and strengthen natural pest regulation (Selvam et al., 2019).

Important Beneficial Birds in Agricultural Fields

Not all birds using bird perches feed on the same type of prey. Their feeding habits vary according to their body structure, beak characteristics, hunting behaviour and active period.

ISSN: 3049-2289

Table 1. Beneficial Birds Commonly Associated with Agricultural Fields and Their Prey

No.	Bird	Main Foraging/Hunting Area	Major Prey
1	Black Drongo	Flying insects above the crop and upper crop canopy	Moths, grasshoppers and other flying insects
2	Common Myna	Ground surface and between crop plants	Caterpillars, grasshoppers and beetles
3	Grey Bushchat	Leaves and small branches	Small insects such as aphids and leafhoppers
4	Greater Coucal	Ground surface and above the crop	Grasshoppers, beetles and larger insects
5	Bee-eater	Flying insects in the air	Moths and other flying insects
6	Cattle Egret	Ground surface and cultivated fields	Grasshoppers and ground-dwelling insects
7	Barn Owl	Field floor and open areas, mainly at night	Rats and mice
8	Spotted Owlet	Ground and open areas during evening and night	Small rodents and large nocturnal insects

Crops Suitable for Bird Perches

Bird perches are not restricted to a particular crop. They can be used in a wide range of agricultural systems, including Rice, Cotton, Maize, Groundnut, Pulses, Millets and Vegetable crops

Bird perches are particularly useful in fields where pest populations include caterpillars, armyworms, stem borers, leaf rollers, grasshoppers and moths. By providing suitable hunting sites, farmers can encourage insectivorous birds to visit and remain in the field.

The contribution of birds may vary depending on the crop, pest complex, surrounding habitat and availability of natural predators.

Types of Bird Perches

Bird perches can be constructed using inexpensive and locally available materials. Several designs can be adapted according to the crop and the bird species that are expected to use them.

1. Bamboo Bird Perch

A small horizontal stick can be attached to the top of a bamboo pole to create a simple perch. Bamboo is inexpensive, widely available and easy to install in crop fields.

2. Dry Branch Perch

Strong dry branches obtained from trees such as neem or gliricidia can be used. Naturally branched dry sticks provide multiple convenient places for birds to land and rest.

3. PVC Pipe Perch

Unused PVC pipes can be combined with a T-joint to create a reusable perch. Because PVC surfaces can be slippery, wrapping the horizontal portion with coir fibre or rope can provide better grip for birds.

4. Rope or Wire Perch

A strong rope or wire can be stretched between two sturdy vertical poles. This design may be useful in crops that are relatively tall or densely planted.

5. T-shaped Bird Perch

The T-shaped perch is one of the simplest and most commonly used designs. A horizontal crossbar is fixed to the top of a vertical pole, providing a suitable resting and observation point for birds such as drongos and bee-eaters.

6. X-shaped Perch

Two sticks can be fixed diagonally across each other at the top of a pole. This provides birds with perching opportunities in different directions and can increase the usable resting space.

7. Owl Perch

An owl perch should be taller, thicker and stronger than a conventional insectivorous bird perch. The primary purpose of an owl perch is to provide an elevated hunting platform from which owls can detect and capture rodents. Research conducted in rice fields in Tamil Nadu found that owl perches were used by Barn Owls and Spotted Owlets for hunting rats; fields with owl perches showed no increase in live rat burrows, whereas fields without perches showed a rapid increase (Gunathilagaraj, 1996).

How Does an Owl Perch Work?

Owls are predominantly nocturnal predators. They often sit on an elevated position and observe the ground for movement. When a rat or mouse is detected, the owl can rapidly swoop down and capture the prey.

Therefore, installing a strong and elevated perch along the field boundary, bund or another suitable open location can provide owls with an effective hunting platform.

Recommended Owl Perch Structure

Feature	Standard Bird Perch	Owl Perch
Overall pole height	1.5–2.5 m	3–4 m
Horizontal crossbar length	30–45 cm	60–75 cm
Crossbar thickness	1.5–2.5 cm	5–10 cm
Suitable material	Bamboo or dry wooden stick	Strong wooden pole or metal pipe
Main purpose	Supporting insectivorous birds	Providing hunting platforms for owls for rodent management

An owl perch should be firmly anchored in the ground so that it does not lean or fall when the bird lands on it. It should preferably be installed in an open location from which the owl can obtain a clear view of a large portion of the field.

Nest Boxes Can Further Support Owls

An owl perch provides a place for hunting, whereas an **owl nest box**, particularly a Barn Owl nest box, can provide a suitable site for resting, nesting and breeding where appropriate.

Protecting large trees, old buildings and other safe natural nesting locations is also important for maintaining owl populations in agricultural landscapes.

How Many Bird Perches Should Be Installed?

The number and spacing of perches can be adjusted according to crop height, field size and local conditions.

Crop Type	Recommended Number per Acre	Approximate Spacing
Short crops such as groundnut and chickpea	15–20	About 15 m
Medium-height crops such as rice and cotton	15–20	About 15 m
Tall crops such as maize and sugarcane	20–25	About 10–12 m
Owl perches	2–3 per acre	Along field boundaries and suitable open areas

Rather than placing all ordinary bird perches in a single straight line, distributing them in a **zig-zag or grid pattern** can help birds monitor different parts of the field more effectively.

The height of the perch is an important consideration. If the perch is too short, the crop canopy may obstruct the bird's view of the field. Therefore, the horizontal crossbar should ideally remain approximately 0.5–1.0 m above the crop canopy.

When Should Bird Perches Be Installed?

Bird perches should preferably be installed **before pest populations become high**, rather than waiting until severe pest damage has already occurred.

In general, bird perches can be installed around **15–20 days after sowing or transplanting**. Early installation gives birds an opportunity to begin using the field before pest populations increase substantially.

Benefits of Bird Perches

Bird perches provide several ecological and practical benefits:

- **Encourage natural enemies:** They support the activity of insectivorous birds and other natural enemies in agricultural landscapes.
- **Support biodiversity:** Encouraging beneficial birds contributes to greater biological diversity within the farm ecosystem.
- **Low-cost technology:** Bamboo, dry branches and other locally available materials can be used, keeping installation costs low.
- **Reduce dependence on chemicals:** Bird perches support IPM approaches that aim to reduce unnecessary pesticide applications.
- **Promote ecological balance:** They help create a more balanced agricultural environment in which birds, natural enemies and other organisms contribute to pest regulation.

- **Support rodent management:** Strong and appropriately designed owl perches can provide hunting platforms for owls and contribute to natural rodent control.

Common Mistakes Farmers Should Avoid

Common Mistake	Possible Problem	Recommended Practice
Installing perches too late	Pest populations may already be high	Install during the early crop growth stage
Using perches that are too short	Crop canopy may block the bird's view	Keep the perch sufficiently above the crop
Using smooth PVC without a gripping surface	Birds may find it difficult to hold the perch	Wrap the horizontal section with coir or rope
Excessive use of highly toxic insecticides	Birds and other natural enemies may be affected	Give priority to IPM and safer pest-management options
Keeping perches until grain maturity without considering bird behaviour	Grain-feeding birds may also use the structures	Remove or modify perches when necessary during crop maturity
Using very thin sticks	The structure may not support larger birds	Use strong, durable dry branches or suitable poles

Integrating Bird Perches into Sustainable Crop Protection

Bird perches should not be considered a stand-alone pest-control technology. They are one component of a broader ecological pest-management strategy that encourages naturally occurring organisms to contribute to pest regulation. Conserving and promoting natural enemies is an important approach to reducing pest pressure and strengthening ecological crop protection (Manikandan & Rengalakshmi, 2023).

Their effectiveness can be enhanced when combined with:

- Conservation of trees and shrubs around agricultural fields
- Protection of natural bird habitats
- Reduced and need-based pesticide application
- Integrated Pest Management (IPM)
- Conservation of other natural enemies such as parasitoids and predatory insects
- Maintenance of field biodiversity
- Protection of suitable nesting and resting sites for birds and owls

Such an approach helps transform the farm from a simplified production area into a more biologically balanced agroecosystem.

Conclusion

Birds are important natural allies in agricultural landscapes. Many species contribute to the regulation of insect pests, while owls and other predators can help manage rodents. However, beneficial birds need suitable habitats and perching sites to remain active in agricultural fields.

Installing simple bird perches is a low-cost and practical way of providing such sites. When combined with the conservation of trees and natural habitats, reduced reliance on unnecessary pesticides

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and adoption of Integrated Pest Management, bird perches can contribute to sustainable and ecologically based crop protection.

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AGRICULTURE BULLETIN

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Plants under pressure: How drought, heat and salinity challenge our crops

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Plants may appear stationary and resilient, but they constantly respond to changes in their environment. Among the greatest challenges facing agriculture today are drought, high temperature and soil salinity. These abiotic stresses can interfere with almost every stage of plant growth, from seed germination and root development to flowering, grain formation and final yield. Drought restricts water availability and causes plants to close their stomata, reducing photosynthesis and increasing the risk of wilting. Heat stress disrupts photosynthetic activity, damages cellular membranes and can severely affect flowering and pollen fertility. Salinity creates both water-deficit and ionic stress, making it difficult for roots to absorb water while allowing toxic levels of sodium and chloride to accumulate in plant tissues. The situation becomes even more complicated when crops experience several stresses simultaneously, as commonly occurs under field conditions. However, plants are not passive victims. They possess sophisticated mechanisms involving deeper roots, osmotic adjustment, antioxidant defence, hormonal signalling and stress-responsive genes that help them survive adverse conditions. Modern crop improvement, precision agriculture, efficient irrigation, soil management and climate-resilient farming practices can strengthen these natural defence mechanisms. Understanding how crops respond to environmental pressure is therefore essential for protecting agricultural productivity and ensuring food security in a changing climate.

Introduction

Agriculture has always depended on a delicate balance among water, temperature, soil and sunlight. When this balance is disturbed, plants come under pressure, and their ability to grow, reproduce and produce yield can be seriously affected. Among the most important environmental challenges facing agriculture today are drought, heat and salinity. These abiotic stresses are becoming increasingly significant as climate change alters rainfall patterns, intensifies temperature extremes and accelerates the degradation of agricultural soils. What was once considered an occasional environmental challenge is increasingly becoming a recurring reality for farmers across different production systems (Konappan *et al*., 2026).

Unlike pests and diseases, which often produce visible symptoms, abiotic stresses can remain hidden within the plant long before their effects become obvious. A crop may appear green and healthy while photosynthesis, water relations and nutrient uptake are already being disrupted. A few days of severe drought or extreme heat during flowering, for example, can interfere with pollen viability, fertilization and grain or fruit development, ultimately causing substantial yield losses. Likewise, the gradual accumulation of salts in agricultural soils can restrict root growth, disturb nutrient balance and reduce crop productivity over successive seasons, often before severe symptoms become visible (Surya *et al*., 2025).

The challenge is particularly complex because plants cannot escape from an unfavourable environment. Unlike animals, they cannot move to a cooler place, search for water elsewhere or avoid a saline patch of soil. Instead, they must adapt to the conditions in which they are rooted. Their roots modify their growth to explore available water and nutrients, leaves regulate water loss through stomata, cells

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accumulate protective compounds to maintain their internal balance, and antioxidant systems become activated to protect cellular components from stress-induced damage. At the molecular level, plants also activate intricate signalling networks involving hormones, stress-responsive proteins and genes that coordinate their responses across different tissues.

More importantly, drought, heat and salinity rarely occur independently in farmers' fields. A period of high temperature may coincide with low soil moisture, while saline soils can further restrict the plant's ability to absorb water. Such combinations create multiple stresses that can be considerably more damaging and complex than individual stresses acting alone.

Understanding how plants sense, respond to and recover from these pressures is therefore no longer confined to plant science laboratories. It has become central to the future of agriculture. For farmers, it can guide better water and soil management; for breeders, it can help identify traits for developing climate-resilient varieties; and for policymakers, it highlights the need for agricultural systems capable of maintaining productivity under increasingly unpredictable environmental conditions. Ultimately, understanding how plants survive under pressure may be one of the keys to securing food production in a changing climate.

When water runs short: The hidden cost of drought

Water is the foundation of plant life. It is required for photosynthesis, nutrient transport, cell expansion and maintenance of cellular structure. When water becomes scarce, the first response is often a reduction in plant water status. Plants attempt to conserve water by closing their stomata, the tiny pores on leaves through which gases move in and out. This helps reduce water loss through transpiration, but it comes at a cost. Closed stomata also restrict the entry of carbon dioxide, reducing photosynthesis and ultimately limiting biomass accumulation and yield (Kithan *et a*l., 2026).

Drought also changes the way plants grow. Root systems may become deeper or more extensively branched as plants attempt to explore a larger volume of soil for available water. Shoots, meanwhile, may grow more slowly. Leaves can become smaller, older leaves may senesce earlier, and severe drought can eventually cause wilting. The timing of drought is particularly important. Water shortage during flowering and grain or fruit development can be far more damaging than drought during some earlier growth stages. In cereals, for example, drought around flowering can reduce pollen viability and grain formation. In pulses and other crops, moisture stress during reproductive development can cause flower and pod abortion (Lizabeni *et al*., 2025).

Plants also activate internal defence systems. They accumulate compounds such as proline, soluble sugars and other osmoprotectants that help maintain cellular water balance. Antioxidant enzymes become active to control reactive oxygen species generated under stress. Thus, drought is not simply a lack of water. It triggers a chain reaction affecting the entire plant.

When temperatures rise: Heat stress and crop productivity

A warm day can be beneficial for crop growth, but excessive temperature can quickly turn from an advantage into a threat. Every crop has an optimum temperature range, and when temperatures rise beyond that range, normal physiological processes begin to decline. High temperatures can disturb photosynthesis by damaging the photosynthetic machinery and altering enzyme activity. Respiration may increase, meaning that plants use more of the energy they have produced. As temperatures continue to rise, the balance between energy production and energy consumption becomes increasingly unfavourable (Paul et al., 2025).

ISSN: 3049-2289

The reproductive stage is particularly vulnerable. Heat during flowering can reduce pollen production, pollen viability and fertilization. Even a crop with healthy leaves and strong vegetative growth may experience a substantial yield reduction if extreme heat occurs during this critical period. Heat stress also increases water loss. Higher atmospheric temperature increases evaporative demand, causing plants to lose water more rapidly through transpiration. Consequently, heat and drought frequently occur together, creating a much greater challenge than either stress alone.

Figure 1. The figure illustrates that how drought, salinity and heat affect the crops

Plants respond by producing heat-shock proteins and activating antioxidant defence systems. These protective mechanisms help maintain the structure and function of proteins and cellular membranes. Some crops also alter their leaf orientation, increase root growth or adjust their flowering time to escape periods of extreme temperature. This is why developing heat-tolerant varieties has become an important goal of modern crop improvement. The figure 1 explains the details on impacts of drought, salinity and heat stress in crops

Salty soils, stressed roots: The challenge of salinity

Salinity is another major threat to agricultural productivity, particularly in areas affected by poor-quality irrigation water, inadequate drainage, seawater intrusion or excessive evaporation. When salts accumulate in the soil, plants face two major problems. First, the high concentration of salts outside the roots makes it more difficult for plants to absorb water. This is known as osmotic stress. Second, ions such as sodium and chloride can enter plant tissues in excessive amounts and become toxic. The roots are therefore among the first parts of the plant to experience the effects of salinity. Root growth may decline, nutrient uptake can become unbalanced, and the movement of water to shoots may be restricted (Konappan *et al.,* 2025).

At the cellular level, excessive sodium can interfere with the uptake and function of essential nutrients such as potassium. High salt concentrations can also disturb membranes, proteins and photosynthetic processes. Yet, plants have several strategies to cope with salinity. Some restrict the entry of sodium into roots, while others transport or compartmentalize excess ions into vacuoles, where they cause less damage. Plants may also accumulate compatible solutes that help maintain water balance without interfering with normal biochemical reactions. From an agricultural perspective, salinity management requires more than simply developing tolerant varieties (Kumar *et al.*, 2025). Proper drainage, efficient irrigation, appropriate water quality, organic matter management and careful fertilizer use can all contribute to reducing the impact of salt accumulation.

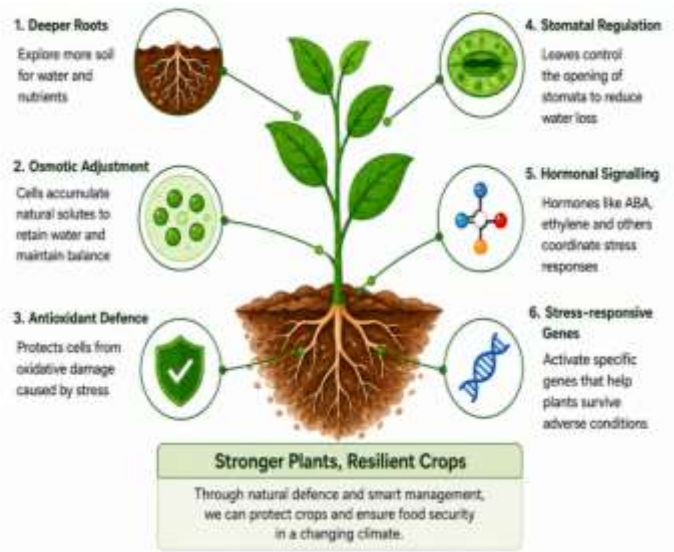

Figure 2. The figure illustrates how plants defend themselves against environmental stress

ISSN: 3049-2289

When stresses strike together: The growing threat of multiple stress

In nature, plants rarely experience only one stress at a time. A farmer may face a season in which rainfall is low, temperatures are unusually high and irrigation water contains elevated salt levels. This combination creates a multiple-stress environment in which plant responses become much more complicated. Drought and heat can occur simultaneously. High temperature increases water demand, while drought limits water availability. Similarly, salinity can intensify the effects of drought because both reduce the plant's ability to maintain adequate water status. Importantly, the response to combined stresses cannot always be predicted simply by adding the effects of individual stresses (Surya *et al*., 2022). Plants may activate unique physiological and molecular responses when stresses occur together. This is one reason why crop testing under controlled conditions alone may not always predict performance in farmers' fields. Future research must increasingly examine crops under realistic combinations of drought, heat, salinity and other environmental pressures. The defense mechanism of plants against the environmental stress given in figure 2.

Building climate-ready crops: From farm practices to plant science

The good news is that plants possess remarkable natural abilities to withstand environmental stress, and scientists are learning how to strengthen these mechanisms. One approach is conventional breeding, where naturally tolerant plants are identified and used to develop improved varieties. Modern molecular breeding can accelerate this process by identifying genes and physiological traits associated with stress tolerance. Advances in genomics, transcriptomics and gene-editing technologies are opening additional opportunities to improve crop resilience.

However, genetics alone cannot solve every problem. Better agricultural management is equally important. Efficient irrigation methods such as drip irrigation can reduce unnecessary water loss. Mulching can conserve soil moisture and moderate soil temperature. Improved drainage can help prevent salt accumulation. Organic matter management can improve soil structure and water-holding capacity (Gowtham *et al.,* 2022). Crop diversification and appropriate planting schedules can also help crops avoid periods of extreme environmental stress. Another promising approach is the development of crops with stronger root systems. Roots are the plant's first interface with the soil and play a central role in acquiring water and nutrients. Deeper and more efficient root systems may allow crops to access water from deeper soil layers during drought.

The future of climate-resilient agriculture will therefore depend on combining plant science with practical farm management. The goal is not simply to make plants survive stress, but to maintain productivity when environmental conditions become unpredictable.

Conclusion

Drought, heat and salinity are more than environmental inconveniences. They are major pressures that can determine whether a crop reaches its yield potential. They affect plants from the roots to the leaves and from early growth to reproduction. Yet, plants possess an extraordinary capacity to sense environmental changes and activate defence mechanisms that help them survive. The challenge for modern agriculture is to understand these natural responses and translate them into practical solutions. Climate-resilient varieties, efficient water management, healthier soils, improved root systems and modern breeding technologies can work together to reduce the impact of abiotic stress. As the climate becomes increasingly unpredictable, the future of food production will depend on crops that can perform not only under ideal conditions, but also under pressure. The plants that feed us will need to become more resilient and our agricultural systems must evolve with them.

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Role of Integrated Farming Systems in Climate-Resilient Agriculture

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Climate change is increasingly threatening agricultural productivity, livestock performance, natural resources, and rural livelihoods through rising temperatures, erratic rainfall, droughts, floods, and other extreme weather events. Integrated Farming Systems (IFS) offer a practical approach to address these challenges by combining crops, livestock, poultry, fisheries, horticulture, agroforestry, and other complementary enterprises within a resource-recycling system. This paper highlights the role of IFS in improving resource-use efficiency, diversifying farm income, enhancing soil health, reducing dependence on external inputs, and strengthening climate resilience. Particular emphasis is given to livestock–crop integration, where crop residues are utilized as feed and livestock manure is recycled as organic fertilizer, creating a circular nutrient flow. The potential of IFS as both an adaptation and mitigation strategy is discussed, along with practical models such as dairy–crop–biogas–vermicompost, duck–fish–rice, goat–agroforestry, and crop–livestock–poultry–horticulture systems. These integrated models can support sustainable, economically viable, and climate-resilient agriculture, particularly for small and marginal farmers.

Introduction

Agriculture today stands at a critical crossroads, facing the dual and interconnected challenges of ensuring food and livelihood security for an ever-growing population while simultaneously mitigating and adapting to the impacts of climate change. The recent episode of heavy rainfall and flooding across Maharashtra serves as a stark reminder of how drastically our climate cycles are being altered. Unpredictable weather patterns, prolonged dry spells followed by intense rainfall, and shifts in cropping seasons are all direct consequences of climate variability and greenhouse gas (GHG) accumulation. These changes not only disrupt agricultural productivity but also threaten soil health, water availability, and biodiversity, thereby endangering the long-term sustainability of rural livelihoods.

In response to these emerging challenges, the Integrated Farming System (IFS) approach has gained significant attention as a sustainable and adaptive model of farming. IFS is based on the principle of biological integration, where crops, livestock, poultry, fisheries, agroforestry, horticulture, and other complementary enterprises are linked in such a way that the by-products or wastes of one component serve as inputs for another. This creates a closed-loop system that minimises external input requirements, recycles farm resources, and reduces environmental pollution. Integrating livestock with crops, in particular, provides multiple advantages. Livestock act as a source of organic manure, which enriches the soil and reduces dependency on chemical fertilizers, while crop residues serve as feed and fodder for animals — creating a sustainable nutrient cycle. The integration also ensures income diversification, reducing farmers' vulnerability to crop failure due to climate shocks. Moreover, mixed farming enhances carbon sequestration through the maintenance of perennial vegetation and organic matter recycling, thereby contributing to climate change mitigation.

In addition, IFS promotes efficient resource use, including better utilization of land, water, and energy. For small and marginal farmers, it offers a steady income throughout the year, improved food and nutritional security, and greater employment opportunities for family labor. By aligning agricultural productivity with ecological stability, IFS represents a holistic strategy for building climate-resilient farming systems that can sustain livelihoods, protect the environment, and ensure long-term food security in a changing climate.

Historical Perspective of Integrated Farming Systems

The concept of integrated farming is not new; traditional smallholder farmers in Asia, Africa, and Latin America have long practised mixed farming systems where livestock and crops co-exist. Ancient rice–fish culture in China, duck–fish–rice systems in Southeast Asia, and crop–livestock–tree systems in India are classic examples. These systems evolved as low-input, closed-loop farming models that recycled nutrients, conserved soil fertility, and diversified household income. During the Green Revolution era, however, farming systems became more specialized and input-intensive, leading to the neglect of these diversified practices. The shift resulted in increased yields but also heightened environmental concerns, including soil degradation, water pollution, and higher carbon footprints. With the growing urgency of climate change, the interest in integrated approaches has resurged, combining traditional wisdom with modern science.

Effects of Climate Change on Agriculture and Livestock

Climate change is placing significant stress on agricultural and livestock production systems, threatening food security and rural livelihoods. Rising temperatures can directly reduce crop yields by affecting plant growth, flowering, and grain formation, while also causing heat stress in livestock. In animals, prolonged exposure to high temperatures can result in reduced milk production, lower fertility, slower growth, and increased susceptibility to diseases. Erratic and unpredictable rainfall further intensifies these challenges by creating water shortages, disrupting sowing and harvesting schedules, and increasing the risk of crop failure. In livestock systems, inadequate rainfall can reduce the availability of pasture, fodder, and drinking water, thereby affecting animal health and productivity. Extreme weather events, including floods, droughts, cyclones, and prolonged dry spells, can cause livestock mortality, damage agricultural land and infrastructure, and accelerate soil erosion and degradation. At the same time, livestock production itself contributes to climate change through greenhouse gas emissions, particularly methane released through enteric fermentation in ruminants and nitrous oxide generated from manure management. If these challenges remain unaddressed, climate change could substantially reduce agricultural productivity and global food availability, with particularly serious consequences for smallholder farmers and livestock-dependent communities in countries such as India.

What is Climate-Resilient Agriculture?

Climate-resilient agriculture (CRA) refers to agricultural approaches and practices that aim to sustainably increase productivity and farmers' incomes while strengthening their capacity to adapt to climate-related challenges and reducing greenhouse gas (GHG) emissions wherever feasible. CRA is based on three interconnected pillars: adaptation, mitigation, and sustainability. Adaptation involves developing and adopting resilient crop varieties, diversified farming systems, improved livestock management practices, and water-conserving technologies to reduce the vulnerability of agricultural systems to climate variability and extreme weather events. Mitigation focuses on reducing GHG emissions per unit of agricultural production through efficient management of water, soil, nutrients, livestock, and other farm resources. Sustainability emphasizes maintaining long-term ecological balance while ensuring stable productivity, profitability, and socio-economic benefits for farming communities. By integrating crops, livestock, trees, fisheries, and other farm enterprises, Integrated Farming Systems (IFS) can make efficient use of available resources, recycle

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farm by-products, diversify income sources, and reduce production risks. Therefore, IFS naturally aligns with the principles of climate-resilient agriculture and represents an important approach for developing productive, adaptive, resource-efficient, and sustainable farming systems.

Necessity of Integrated Farming Systems in the Climate Changing Era

Integrated Farming Systems (IFS) have become an important approach for making farming more resilient, resource-efficient, and sustainable. Farmers today face challenges such as declining soil fertility, water scarcity, rising production costs, and increasing uncertainty in farm productivity. In such a situation, depending on a single crop or farming activity can increase the risk of income loss. IFS addresses these challenges by combining crop production with suitable enterprises such as dairy, goat and sheep rearing, poultry, fisheries, horticulture, fodder production, and composting. These enterprises are interconnected, allowing the output or waste from one component to serve as an input for another. For example, crop residues can be used as livestock feed, while animal dung can be converted into organic manure for crop production. This efficient recycling of farm resources reduces waste and dependence on costly external inputs.

Another major advantage of IFS is the diversification of farm income. When one enterprise performs poorly, income from other components can help support the farmer's livelihood. Livestock, poultry, dairy, and other allied activities can provide regular or frequent income, complementing the seasonal returns obtained from crops. An integrated farm can also produce a wide range of food products, including cereals, pulses, milk, meat, eggs, fruits, and vegetables, thereby contributing to household food and nutritional security.

IFS also supports long-term soil and environmental health by improving organic matter, recycling nutrients, conserving resources, and increasing soil organic carbon. Thus, IFS functions as both an adaptation and mitigation strategy. It strengthens farmers' capacity to manage production risks while improving resource-use efficiency, reducing dependence on external inputs, and enhancing carbon storage. Therefore, integrating multiple farm enterprises is not merely a diversification strategy but a practical pathway towards resilient, economically viable, and environmentally sustainable agriculture.

Livestock-Crop Integration: A Pathway to Climate Resilience

The integration of livestock and crop production is a fundamental component of Integrated Farming Systems (IFS) and represents an important pathway for enhancing climate resilience, particularly among small and marginal farmers. By combining crop and livestock enterprises, farmers can improve resource-use efficiency, recycle nutrients, diversify income sources, and reduce vulnerability to climate-related risks. One of the major advantages of livestock-crop integration is the efficient recycling of farm resources. Livestock manure can be converted into valuable organic fertilizer, improving soil fertility and reducing dependence on costly synthetic fertilizers. Similarly, crop residues such as straw, husks, stovers, and other by-products can be utilized as livestock feed, thereby reducing waste and creating a circular flow of nutrients within the farming system. Water resources can also be used more efficiently through the appropriate utilization of livestock wastewater for irrigation and biogas slurry as an organic soil amendment.

Livestock-crop integration can further contribute to reducing the environmental footprint of agriculture. Improved manure management through composting, vermicomposting, and biogas production can reduce greenhouse gas emissions while producing useful inputs such as organic manure and renewable energy. Agroforestry-livestock systems can enhance carbon sequestration by storing carbon in trees, vegetation, and soils. In addition, improved feeding practices, balanced diets, better fodder quality, and appropriate

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breeding strategies can improve livestock productivity and potentially reduce enteric methane emissions per unit of animal product. Diversification of crop and livestock enterprises also strengthens farm-level risk management and income stability. During droughts, floods, pest outbreaks, or other climate-related crop losses, livestock can provide an alternative source of income through milk, meat, eggs, manure, and other products. Multiple enterprises also distribute production and market risks across different seasons and income sources.

The integration of livestock contributes significantly to maintaining soil health and long-term productivity. Regular application of organic manure increases soil organic matter, improves soil structure and water-holding capacity, and supports beneficial microbial activity. Integration of fodder crops with rotational grazing can further reduce soil degradation and improve land-use efficiency. Overall, IFS promotes sustainable intensification by generating greater and more stable production from available land, water, labour, and other resources. Models such as dairy-crop, poultry-horticulture, goat-agroforestry, and crop-livestock systems therefore offer practical opportunities for developing productive, resource-efficient, economically viable, and climate-resilient agricultural systems.

Practical Models for Climate-Resilient Integrated Farming Systems

Climate-resilient Integrated Farming Systems (IFS) combine different agricultural enterprises in a way that improves resource-use efficiency, reduces climate-related risks, and provides stable income to farming households. By recycling farm wastes and utilizing available land, water, labour, and biomass efficiently, these systems can improve both productivity and sustainability. Several practical IFS models are particularly suitable for small and marginal farmers.

A. **Dairy + Crop + Biogas + Vermicompost:** This model integrates dairy animals with crop production, biogas generation, and vermicomposting. For example, a farmer maintaining two to four dairy cows or buffaloes can collect animal dung and use it in a small biogas unit for cooking or farm energy. The digested slurry can be used for vermicomposting or directly applied to crop fields as an organic fertilizer. Crop residues such as maize stover, sorghum straw, and wheat straw can be used as livestock feed. This creates a closed nutrient cycle, reduces dependence on chemical fertilizers, and provides both energy and organic manure.

B. **Duck–Fish–Rice Farming:** In suitable lowland areas, rice cultivation can be combined with duck and fish production. Ducks forage for insects, weeds, and other organisms in rice fields, reducing the need for chemical pesticides. Their droppings add nutrients to the field and support natural productivity, while fish feed on aquatic organisms and organic residues. For example, farmers in rice-growing regions can rear ducks and compatible fish species alongside paddy, obtaining rice, eggs, duck meat, and fish from the same land and water resources.

C. **Goat + Agroforestry Systems:** Goat production can be integrated with trees, shrubs, grasses, and fodder crops. Trees such as *Leucaena*, *Gliricidia*, and other locally suitable fodder species can provide nutritious feed while also contributing to soil conservation and carbon sequestration. Farmers can obtain goat meat, fodder, fuelwood, and additional tree products from the same farm.

D. **Crop–Livestock–Poultry–Horticulture Mix:** This diversified model combines field crops, livestock, poultry, vegetables, fruits, and fodder crops. For example, crop residues can feed cattle, poultry manure can fertilize vegetable plots, and livestock manure can support fruit trees. Income from milk, eggs, vegetables, fruits, and grains provides year-round cash flow and improves household nutritional security.

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These practical models demonstrate how integrated farming can transform farm wastes into useful resources, diversify income, reduce production risks, and strengthen resilience to climate variability while supporting sustainable agricultural development.

Conclusion

The increasing frequency and unpredictability of climate-related stresses highlight the limitations of farming systems that depend heavily on a single crop or enterprise. Agriculture therefore needs approaches that can simultaneously address productivity, profitability, resource efficiency, environmental sustainability, and climate risks. Integrated Farming Systems provide such an approach by connecting crops, livestock, poultry, fisheries, horticulture, agroforestry, fodder production, composting, and other enterprises within a mutually supportive system. The basic principle is to convert farm by-products and wastes into useful resources, thereby reducing external input requirements and closing nutrient and resource cycles. The integration of livestock with crops is particularly valuable because it links crop residues with animal feed and animal manure with soil fertility. Additional components such as biogas, vermicomposting, agroforestry, poultry, fisheries, and horticulture can further improve resource-use efficiency, diversify farm income, and strengthen resilience. Practical models such as dairy–crop–biogas–vermicompost, duck–fish–rice, goat–agroforestry, and crop–livestock–poultry–horticulture systems demonstrate how these principles can be applied at the farm level. By combining productivity with resource recycling, income diversification, soil improvement, and environmental benefits, IFS offers a practical pathway towards climate-resilient, economically viable, and sustainable agriculture, particularly for small and marginal farming households.

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Drip Irrigation in Horticulture: More Crop per Drop

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Water scarcity has become a major challenge for sustainable horticultural production due to climate change, erratic rainfall, declining groundwater resources, and increasing competition for water use. Horticultural crops such as fruits, vegetables, flowers, and plantation crops require precise and timely irrigation for optimum growth, yield, and quality, while conventional irrigation methods often lead to substantial water losses through evaporation, runoff, and deep percolation. Drip irrigation has emerged as an efficient and resource-conserving technology that delivers water directly to the root zone, thereby maximizing water-use efficiency and minimizing wastage. The system promotes better crop growth, higher productivity, improved produce quality, efficient fertilizer use through fertigation, reduced weed growth, and lower labour requirements. Its adoption in horticultural crops has demonstrated significant savings in water and fertilizers along with enhanced economic returns. With growing concerns over water security and climate resilience, drip irrigation is increasingly recognized as a key technology for sustainable horticulture and profitable farming, truly embodying the principle of "More Crop per Drop."

What is Drip Irrigation?

Drip irrigation, also known as trickle irrigation, is a micro-irrigation system that delivers water directly to the root zone of plants through a network of pipes, tubes, valves, and emitters. Unlike conventional irrigation methods that wet the entire field surface, drip irrigation applies water slowly and precisely where it is needed most. This targeted approach minimizes wastage and ensures efficient water use.

When and Where Drip Irrigation Should Be Used

Drip irrigation, also known as trickle irrigation, is a micro-irrigation method in which water is applied at a very low rate directly near the plant root zone through a network of small plastic pipes fitted with emitters or drippers. The discharge from each emitter is generally only a few litres per hour, and irrigation is provided frequently, often every one to three days. Unlike surface or sprinkler irrigation, which wets the entire soil surface, drip irrigation wets only the portion of soil where active roots are concentrated. This creates a favourable moisture environment that promotes healthy root growth and efficient water use.

Suitable Crops

Drip irrigation is especially suitable for high-value horticultural crops such as fruits, vegetables, flowers, vines, and plantation crops. Row crops like tomato, chilli, cucumber, capsicum, and strawberry respond particularly well to drip irrigation, while tree crops such as mango, citrus, pomegranate, guava, banana, grape, and papaya can be irrigated efficiently by providing one or more emitters to each plant. Because the initial installation cost is relatively high, the technology is generally most economical for crops with high market value and high water-use efficiency requirements.

Suitable Land Conditions

One of the major advantages of drip irrigation is its adaptability to a wide range of land slopes. It can be used effectively on flat, undulating, and moderately sloping fields. In sloping areas, crops are usually planted along contour lines and lateral pipes are laid along the contour to minimize pressure variations and ensure uniform water distribution.

Suitable Soil Types

Drip irrigation performs well in most soil types. In heavy clay soils, water should be applied slowly to avoid ponding and surface runoff. In sandy soils, where water moves rapidly downward, higher emitter discharge rates or closer emitter spacing may be required to achieve adequate lateral wetting of the root zone. Proper system design according to soil texture is therefore essential for efficient irrigation.

Suitable Irrigation Water

The quality of irrigation water is particularly important in drip systems because emitters contain very small openings that can easily become clogged by sediments, algae, fertilizer deposits, or precipitated salts such as calcium and iron. For this reason, filtration is an essential component of every drip irrigation system. Screen filters and sand filters are commonly used to remove suspended particles before water enters the lateral pipes. Regular maintenance and flushing of the system are necessary to prevent blockage and maintain uniform discharge.

Interestingly, drip irrigation is often more suitable than other irrigation methods when water quality is marginal or moderately saline. Since water is delivered directly to the root zone and in small quantities, salt accumulation around the root zone can be managed more effectively, and overall water-use efficiency remains high.

Components of a Drip Irrigation System

A typical drip irrigation system consists of several important components working together to deliver water precisely to the crop:

- **Pump unit:** lifts water from the source and provides the required operating pressure.
- **Control head:** includes valves, pressure regulators, and filters, and may also contain a fertigation tank for injecting fertilizers into the irrigation water.
- **Mainline and sub-mainline:** carry water from the pump to different sections of the field.
- **Laterals:** small polyethylene pipes that distribute water near the plants.
- **Emitters or drippers:** devices that release water slowly and uniformly to the root zone.

The integration of a fertilizer tank with the control head is one of the most important advantages of drip irrigation because it allows precise application of nutrients through fertigation.

Operation and Wetting Pattern

Drip systems are usually permanent installations and can be operated manually or automatically. Frequent irrigation maintains a favourable moisture level around the roots, resulting in vigorous crop growth and better nutrient uptake. However, because plants receive water regularly, they may develop relatively shallow roots; therefore, system maintenance is critical and interruptions in irrigation should be avoided.

The shape of the wetted soil zone depends mainly on soil texture and emitter discharge. In sandy soils, water tends to move downward, producing a narrow and deep wetting pattern, whereas in clay soils water spreads more sideways, creating a wider and shallower wetted zone. Proper selection of emitter spacing and discharge rate is essential to ensure that the entire active root zone receives adequate moisture.

It is important to understand that drip irrigation does **not** reduce the actual water requirement of the crop. The crop still needs its full water requirement for normal growth. The water savings achieved through drip irrigation come from reduced evaporation, runoff, and deep percolation losses. Therefore, the efficiency of drip irrigation depends not only on the equipment but also on proper management by the farmer.

Best Situations for Drip Irrigation

Drip irrigation is particularly advantageous in areas where:

- water is scarce or expensive,
- irrigation water is of marginal quality,
- land is undulating or sloping,
- labour availability is limited,
- fertilizer costs are high, and
- high-value horticultural crops require frequent irrigation.

Under these conditions, drip irrigation offers substantial savings in water and fertilizers while improving yield, quality, and farm profitability. It should be viewed not as a replacement for all irrigation methods, but as a highly efficient alternative for situations where precise water and nutrient management is essential.

Advantages of Drip Irrigation

- **Water Conservation:** One of the greatest advantages of drip irrigation is its ability to save water. Compared with conventional surface irrigation methods, drip systems can reduce water consumption by 30–70 percent. Since water is delivered directly to the root zone, losses through evaporation and runoff are significantly minimized.
- **Increased Crop Yield:** Maintaining optimum soil moisture throughout the growing season promotes better root development, nutrient uptake, flowering, and fruit growth. Many studies have demonstrated yield increases ranging from 20 to 50 percent in various horticultural crops under drip irrigation.
- **Improved Fruit and Vegetable Quality:** Uniform water supply helps produce fruits and vegetables of better size, colour, flavour, and market quality. Crops such as grapes, pomegranate, mango, citrus, tomato, capsicum, and cucumber often show remarkable improvements in quality when irrigated through drip systems.
- **Efficient Fertilizer Use:** Drip irrigation facilitates fertigation—the application of fertilizers through irrigation water. Nutrients can be supplied directly to the active root zone in small and frequent doses, improving fertilizer-use efficiency and reducing nutrient losses.
- **Reduced Weed Growth:** Since only a limited portion of the soil surface is wetted, weed growth is substantially reduced compared with flood irrigation. This lowers labour costs associated with weeding and field maintenance.
- **Lower Disease Incidence:** By avoiding excessive wetting of foliage and the soil surface, drip irrigation helps reduce the incidence of fungal and bacterial diseases that thrive under moist conditions.
- **Labour and Energy Savings:** Automated drip systems require less labour for irrigation management and often reduce pumping costs due to efficient water application.

Drip Irrigation in Major Horticultural Crops

Fruit Crops: Drip irrigation has been extensively adopted in perennial fruit crops such as mango (*Mangifera indica*), citrus (*Citrus* spp.), pomegranate (*Punica granatum*), guava (*Psidium guajava*), banana (*Musa* spp.), grape (*Vitis vinifera*), papaya (*Carica papaya*), and apple (*Malus domestica*) owing to its superior water-use efficiency and precise root-zone moisture management. Maintenance of optimum soil moisture under drip irrigation enhances root proliferation, canopy architecture, photosynthetic efficiency, flowering intensity, fruit set, fruit retention, and fruit enlargement, ultimately resulting in higher marketable yield. In banana, drip irrigation integrated with fertigation has been shown to significantly increase bunch weight, finger size, nutrient-use efficiency, and overall productivity while reducing irrigation water consumption. In

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grapevine, regulated drip irrigation improves berry size, total soluble solids, sugar accumulation, colour development, and phenolic composition, thereby enhancing both fresh fruit quality and processing value.

Vegetable Crops: Vegetable crops possess relatively shallow and active root systems and therefore respond markedly to frequent and precise irrigation scheduling. Crops such as tomato (*Solanum lycopersicum*), chilli (*Capsicum annuum*), brinjal (*Solanum melongena*), cucumber (*Cucumis sativus*), onion (*Allium cepa*), and cabbage (*Brassica oleracea*) exhibit substantial improvements in growth, yield, and water productivity under drip irrigation. Uniform moisture supply minimizes fluctuations in soil water potential, thereby reducing the incidence of physiological disorders such as fruit cracking, blossom-end rot, tip burn, and bolting. Drip irrigation also improves nutrient uptake efficiency, reduces weed infestation in the inter-row area, and facilitates fertigation-based precision nutrient management, contributing to enhanced crop productivity and quality.

Floriculture Crops: Commercial floriculture species including rose (*Rosa* spp.), gerbera (*Gerbera jamesonii*), carnation (*Dianthus caryophyllus*), chrysanthemum (*Chrysanthemum* spp.), and marigold (*Tagetes* spp.) require a continuously favourable soil moisture regime for optimum vegetative growth and flower production. Drip irrigation maintains a stable rhizosphere environment, promotes efficient nutrient absorption, and minimizes moisture stress during critical stages of bud initiation and flower development. Consequently, improvements are observed in flower stem length, bud size, flower diameter, colour intensity, vase life, and overall market quality. The localized irrigation also reduces foliar wetting and humidity around the canopy, thereby lowering the incidence of fungal diseases and improving the economic returns of commercial flower production systems.

Fertigation: A Powerful Combination

One of the greatest strengths of drip irrigation is its seamless integration with fertigation, a precision nutrient-management practice in which water-soluble fertilizers are delivered directly through the irrigation system. This approach ensures that both water and nutrients reach the active root zone in a controlled and timely manner, allowing plants to absorb them more efficiently. Unlike conventional fertilizer application, where a significant portion of nutrients may be lost through leaching, runoff, or volatilization, fertigation supplies nutrients in small and frequent doses that closely match the crop's growth requirements.

As a result, fertigation significantly enhances nutrient-use efficiency, minimizes fertilizer wastage, and ensures uniform nutrient distribution throughout the field. Crops receive a continuous and balanced supply of essential nutrients, leading to vigorous growth, improved flowering and fruit set, higher yields, and superior produce quality. In addition, fertigation reduces labour requirements and lowers the cost of fertilizer application, making nutrient management more economical and environmentally sustainable.

For high-value horticultural crops such as fruits, vegetables, flowers, and plantation crops, where precise nutrient management directly influences yield, quality, and market returns, fertigation has become an indispensable component of modern horticulture. By combining efficient irrigation with efficient nutrition, fertigation truly represents a smart farming practice that maximizes productivity while conserving both water and fertilizers.

Challenges in Adoption

Despite its numerous advantages, the adoption of drip irrigation faces certain challenges:

- High initial installation cost

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- Requirement for clean water sources
- Emitter clogging due to poor filtration
- Need for technical knowledge and maintenance
- Limited awareness among small and marginal farmers

However, government subsidy schemes and technological advancements are making drip irrigation increasingly affordable and accessible.

Government Support for Micro-Irrigation

Recognizing the urgent need for water conservation and efficient irrigation, the Government of India has been actively promoting drip and sprinkler irrigation through the Pradhan Mantri Krishi Sinchayee Yojana (PMKSY) and its Per Drop More Crop (PDMC) component. The scheme aims to improve on-farm water-use efficiency, expand micro-irrigation coverage, and encourage precision farming practices. Small and marginal farmers receive 55% financial assistance for installing micro-irrigation systems, while other farmers receive 45% assistance on the approved unit cost. The scale of the programme has expanded significantly during the last decade. According to the Ministry of Agriculture and Farmers Welfare, more than 110.92 lakh hectares have been brought under micro-irrigation since the inception of PDMC, covering nearly 8% of India's net sown area, and about 9.3 lakh farmers receive support every year under the programme. The government has also strengthened financial support for irrigation infrastructure. PMKSY has received central assistance exceeding ₹64,407 crore over the past decade, benefiting more than 27 million farmers and creating or restoring irrigation potential across 24.61 million hectares. In the Union Budget 2026–27, an allocation of ₹6,587 crore was made for PMKSY to further expand irrigation coverage, improve water-use efficiency, and promote sustainable water management. In addition, an initial outlay of ₹1,600 crore has been approved for the Modernization of Command Area Development and Water Management (M-CADWM) component, which supports pressurized piped and micro-irrigation systems at the farm level. To accelerate adoption, the government has also created a Micro Irrigation Fund through NABARD, enabling states to implement large-scale drip irrigation programmes. Several states, including Karnataka, Andhra Pradesh, Maharashtra, Gujarat, and Tamil Nadu, provide additional state subsidies and technical support for horticultural crops. These initiatives are helping farmers reduce irrigation water use, improve fertilizer-use efficiency through fertigation, increase crop productivity, and build resilience against drought and climate variability.

Future Prospects

The future of horticulture will depend heavily on efficient resource management. With increasing water scarcity and climate variability, precision irrigation technologies such as drip irrigation will play a crucial role in sustainable crop production. The integration of drip systems with sensors, automation, artificial intelligence, and Internet of Things (IoT)-based technologies is opening new possibilities for precision horticulture. Smart irrigation systems can monitor soil moisture in real time and apply water only when required, further improving efficiency and productivity.

Conclusion

Drip irrigation represents one of the most important technological advancements in modern horticulture. By delivering water directly to the root zone, it maximizes water-use efficiency, enhances crop productivity, improves produce quality, and reduces input costs. As water resources become increasingly scarce, adopting drip irrigation is not merely an option but a necessity for sustainable horticultural development. The principle of **"More Crop per Drop"** perfectly captures its potential to ensure higher productivity, greater profitability, and long-term environmental sustainability. Through wider adoption of drip irrigation, farmers can secure better

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livelihoods while conserving one of nature's most precious resources—water.

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Waste-to-Bloom: Growing Ornamental Flowers on Kitchen and Municipal Organic Waste

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Rapid urbanization and population growth have sharply increased the volume of kitchen and municipal solid waste generated worldwide, much of which is biodegradable and suitable for recycling into valuable soil amendments. This article reviews the concept of "waste to bloom" - the conversion of kitchen scraps and municipal organic waste into compost that can be used as a growing medium for ornamental flowering plants. It discusses waste characterisation, composting and vermicomposting methods suitable for households and municipalities, the suitability of resulting composts for common ornamental species such as marigold, petunia, dusty miller and begonia, the environmental and economic benefits of this practice, and the challenges that must be managed, including salinity, heavy metal content and immature compost phytotoxicity.

Introduction

The fast growth of cities and the increasing population have resulted in a significant rise in the generation of organic waste from households, restaurants, vegetable markets and other municipal sources. This organic waste mostly piles up in landfills or open dumps. This not only looks bad but also causes many problems, such as foul smell and pollution of soil and water. Worse still, we are throwing away something that could actually be useful. It is therefore clear that we need more sustainable ways to handle waste while also improving our surroundings.

Organic waste does not have to be a problem when it is managed properly. It decomposes naturally into nutrient-rich compost. This compost does wonders for soil: it boosts fertility, supports microbial life, helps soil hold water better, and supplies the nutrients and micronutrients that plants need to thrive. It takes something we normally throw away and turns it into something valuable. Indian households generate an average of 55 kg of food waste per capita annually, adding up to a staggering 78.2 million tons across the country each year (Food Waste Index Report 2024, UNEP, cited by WRI India).

The Waste We Throw Away: Facts

Before getting into compost bins and marigolds, it helps to look at what actually makes up the waste stream, because the answer is more lopsided than most people expect. In a typical Indian city, over half of municipal solid waste by weight is biodegradable - kitchen scraps, garden trimmings, market waste and similar material. The remainder is a mix of recyclables, inert debris and material that has no business being in a compost pile. Understanding this composition is important because separating biodegradable waste at source is the first step towards efficient composting and converting everyday kitchen waste into a useful resource.

Table 1. Different types of municipal solid waste

Waste Fraction	Typical Share (% by weight)	Common Sources
Biodegradable/ Organic	50-55%	Kitchen scraps, garden waste, market refuse
Plastics	8-10%	Packing, carry bags, wrappers

Paper and Cardboard	5-7%	Packaging, newspapers
Glass	2-3%	Bottles, containers
Metals	1-2%	Cans, foils
Inert/Silt/Debris	20-25%	Construction dust, ash, street sweepings

From Kitchen Scraps to Compost Gold

What Kitchen Waste Works Best

Not all kitchen waste is equally useful for composting, but a wide variety of scraps can be recycled into rich organic matter:

- Fruit and vegetable peels (banana, potato, carrot, cucumber) - rich in potassium and micronutrients.
- Eggshells - a natural source of calcium, useful for strengthening plant cell walls.
- Tea leaves and coffee grounds - add nitrogen and improve soil texture.
- Onion and garlic skins -contain sulphur compounds that can prevent certain pests.
- Citrus peels (in moderation) - add acidity, useful for acid-loving ornamentals like hydrangeas.

Items to avoid in home compost include cooked food with oil, dairy, and meat, as these attract pests and produce foul odours during decomposition.

Municipal Waste: Scaling Up the Bloom

While home composting handles kitchen waste at a small scale, cities generate far larger volumes of organic waste through markets, parks, and households collectively. Municipal solid waste management programs increasingly incorporate composting as a core strategy.

Segregated Waste Collection: Successful waste-to-bloom programs begin with source segregation - separating biodegradable waste (food scraps, garden trimmings, market refuse) from non-biodegradable waste (plastics, metals, glass) before collection. Many cities now mandate color-coded bins for this purpose.

Centralized Composting Facilities: Biodegradable municipal waste is transported to composting plants where it undergoes controlled decomposition using windrow composting (long, turned piles) or in-vessel composting (enclosed mechanical systems). The resulting compost is tested for quality and made available to municipal parks departments, nurseries, and citizens - often at subsidized rates - to grow ornamental gardens, roadside plantings, and public parks.

Flower Beds from City Waste: Many municipalities now use compost derived from city waste to landscape. Public parks and traffic roundabouts are often filled with marigolds, petunias, and seasonal bedding flowers. Roadside avenues are planted with flowering shrubs like hibiscus and bougainvillea. Community gardens let residents collect free compost for home flower beds. Some cities have gone further, launching dedicated “Waste to Bloom” or “Garden from Garbage” campaigns encouraging citizens to grow ornamental plants using compost made from their own segregated waste, closing the nutrient loop at a hyperlocal level.

Turning Waste into Planting Media

The processing of composting is essentially controlled decomposition. Microorganisms such as bacteria, fungi, actinomycetes and other microbes generate heat and release CO_2 and water vapour and eventually leave behind a dark, crumbly, humus-rich substance. This process mainly needs oxygen, a good moisture level and a C: N ratio of roughly 25:1 to 30:1. For this kitchen waste is a good example of this. Vegetable peels and used tea leaves are nitrogen-rich so when piled up with dry, shredded cardboard, sawdust and similar carbon-rich material, they break down easily and efficiently. Municipal-scale

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composting runs on the same principle but at a higher scale. Before the process begins, the material must first be sorted and other items such as glass and plastic pulled out, as these do not decompose and will contaminate the finished compost if left in.

The Composting Process

Collection and Segregation - Separate wet kitchen waste from dry waste (paper, cardboard, dried leaves) at the source.

Layering - Alternate "green" nitrogen-rich waste (vegetable scraps) with "brown" carbon-rich waste (dry leaves, shredded paper) in roughly equal parts.

Aeration - Turn the pile every few days to introduce oxygen, which speeds decomposition and prevents bad odour.

Moisture Control - Keep the pile as damp as a drained sponge- not soggy, not bone dry.

Maturation - Over 6-8 weeks (or faster with vermicomposting using earthworms), the waste transforms into dark, crumbly, earthy-smelling compost rich in nitrogen, phosphorus, and potassium- exactly what flowering plants need for strong roots, lush foliage, and abundant blooms.

The Process of Vermicomposting

One can also opt for vermicomposting, where species such as *Eisenia fetida, Perionyx excavatus, Eudrilus eugeniae* and *Polypheretima elongata* are used. These worms break down organic waste directly and decompose material much faster than microbes alone, producing compost that is finer, more even, and richer in beneficial microbes. Managing them takes a little more care, as they are more sensitive to temperature swings and will not tolerate a pile that overheats- but the end product is always considered a premium growing amendment. Species selection matters for this outcome, since different earthworm taxa vary in feeding rate, temperature tolerance and processing efficiency, which in turn shapes the biology and management of the whole vermicomposting operation (Domínguez and Edwards, Vermiculture Technology, CRC Press).

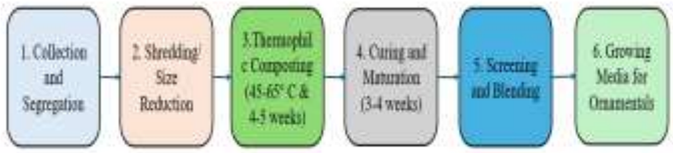

Figure 1. Stages in converting kitchen and municipal waste into a growing medium

Across all these processes, a hot thermophilic phase (45-65°C) generally kills most weed seeds and pathogens, followed by a longer curing or maturation phase in which the material stabilizes and any phytotoxic substances break down. Skipping the curing step is a common mistake in small-scale composting, and the easiest one to avoid, since it simply requires patience.

Challenges and Solutions

Contamination in Municipal Waste Streams

Municipal solid waste, even when labelled ‘organic,’ is rarely as clean as kitchen waste collected directly from a household. Shards of plastic, glass and grit routinely turn up in poorly segregated municipal compost, and screening it out adds a labour cost that is easy to underestimate. Fine plastic fragments in particular are difficult to remove completely and are an active area of concern in the broader compost-quality literature.

Salinity and Electrical Conductivity

The Municipal solid waste compost in this trial had noticeably higher salinity than the kitchen-waste or vermicompost treatments, likely a result of the more varied and less controlled input stream, including food waste with high salt content. High EC can be tough on young seedlings and shallow-rooted ornamentals, though most established flowering plants tolerate it reasonably well once diluted with soil.

Pathogens and Odour

A properly managed thermophilic composting phase should kill the vast majority of plant and human pathogens. Piles that are not turned regularly or that stay too wet can develop anaerobic pockets, leading to foul odours and incomplete pathogen kill- a common complaint that gives composting a bad reputation it does not always deserve. Maintaining the right balance of moisture, aeration and temperature is therefore essential to control odour and ensure effective pathogen reduction during composting.

Heavy Metal Accumulation

Municipal waste streams can also carry trace amounts of lead, zinc, cadmium and copper mainly from batteries, packaging and other non-organic material that slips past segregation. Interestingly, the composting process itself is not just a passive risk here: earthworm-driven vermicomposting has been shown to substantially lower the heavy metal content of urban solid waste, since the worms absorb metal ions through their digestive tract as they process the material (Pattnaik and Reddy, 2011).

Immature Compost and Phytotoxicity

Using compost before it has fully cured is probably the single most common mistake at the household level. Immature compost can release organic acids and ammonia that actively harm young roots. Standard maturity indices such as the C:N ratio, germination index and residual self-heating capacity give a practical way to judge, rather than guess, whether a given batch is actually ready to use (Bernal et al., 2009).

Best Ornamental Flowers for Waste-Based Growing

- Marigold - thrives in vermicompost and moderate Municipal Solid Waste Compost blends though seedling emergence and growth decline once Municipal Solid Waste compost content rises above about 30% of the substrate (Tzortzakis et al., 2012).
- Calendula - improved height and flower count at ~20% vermicompost, with better performance maintained even under saline growing conditions (Adamipour et al., 2019).
- Petunias- improved germination/flowering with manure, food waste, and paper waste vermicompost with flower numbers rising significantly at 20-40% substitution into the growing medium (Arancon et al., 2008).
- Roses, chrysanthemums -benefit from compost-enriched mixes as a peat substitute part of a wider pattern in which vermicompost- and compost-amended container media consistently outperform unamended peat across ornamental species (Atiyeh et al., 2000).
- Dusty miller (*Senecio cineraria*) - tolerant across a wide range of compost blends.
- Begonia (*Begonia* × *Semperflorens-cultorum*)- responsive to blended soilless substrates.
- Zinnia - thrives in compost-enriched beds and blooms prolifically.
- Cosmos - grows well in poorer soils enriched with organic matter.
- Sunflower - excellent for utilizing large volumes of compost and biodegraded waste.
- Hibiscus - common in municipal landscaping using city compost.
- Basil and other companion ornamentals/aromatics- grown successfully in MSWC-peat mixes.

Beyond Compost: Other Waste-to-Bloom Techniques

Mulching

Dried leaves, grass clippings and shredded paper waste can be applied directly as mulch around flowering plants. Mulch conserves soil moisture, suppresses weeds, regulates soil temperature and slowly breaks down to enrich the soil - all while reducing the volume of waste sent to landfills.

Biochar

Charred organic waste (biochar), produced through controlled low-oxygen burning of garden and agricultural residue, can be mixed into soil to improve aeration, water retention, and nutrient availability - creating better growing conditions for ornamentals, especially in compacted urban soils. Beyond improving soil structure, biochar can also help retain nutrients and carbon in the soil, making it a useful component of sustainable waste management and urban horticulture.

Repurposed Containers

Beyond nutrients, waste materials themselves can serve as planters. Used tin cans, plastic bottles, broken ceramic pots, and even old tires are commonly upcycled into decorative flower containers, adding an aesthetic and environmental dimension to the waste-to-bloom movement.

Benefits of the Waste-to-Bloom Approach

- Diverts biodegradable waste away from landfills, reducing methane generation and remove pollution, a saving that shows up clearly when the greenhouse-gas balance of composting is weighed against landfilling in life-cycle terms (Boldrin et al., 2009)
- Reduces dependence on non-renewable peat and synthetic fertilizers in ornamental horticulture.
- Improves soil structure, water-holding capacity and microbial activity in growing media.
- Offers a low-cost substrate option for household gardeners, nurseries and municipal green-space programmes.
- Creates income and livelihood opportunities through small-scale compost and vermicompost enterprises.
- Recycles nutrients (nitrogen, phosphorus and potassium and micronutrients) back into productive use.

Conclusion

The "waste to bloom" concept demonstrates that everyday kitchen scraps and municipal organic waste need not be viewed solely as a disposal problem but can instead serve as a renewable input for ornamental horticulture. Composting and vermicomposting technologies, ranging from simple household bins to municipal-scale facilities, can convert this waste into a nutrient-rich growing medium capable of supporting the cultivation of marigold, petunia, dusty miller, begonia and other flowering ornamentals. Realising this potential at scale requires attention to waste segregation, composting process control, compost maturation and species-specific blend ratios, but the environmental and economic benefits- reduced landfill burden, resource recycling and lower dependence on peat-based substrates- make the waste-to-bloom pathway a practical contribution to sustainable urban horticulture.

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Recent Advances on Plant Growth Promoter and Retardants in Fruit Crops

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The regulation of fruit crop growth, development and productivity is largely dependent on plant growth regulators or PGRs. These substances, covering both natural phytohormones and synthetic regulators, regulate essential physiological processes like cell division, cell elongation, blooming, fruit set, development and ripening. Recent improvements emphasize their function in boosting fruit crop performance under normal and stress circumstances. Auxins, gibberellins, cytokinins, abscisic acid, ethylene, salicylic acid and jasmonates are examples of common PGRs that are frequently utilized to enhance fruit output and quality, optimize canopy design and increase resistance to abiotic stress. Additionally, they allow cutting-edge uses such *invitro* plant propagation, which frequently interacts with light conditions and phytoremediation of polluted soils. Additionally, PGRs control metabolic pathways and hormonal balance to govern fruit development phases. Using PGRs after harvest increases shelf life, regulates ripening, postpones senescence, and lowers the incidence of illness. All things considered, combining growth promoters and retardants offers a viable and efficient way to improve fruit crop yield, quality and economic value

Introduction

Plant hormones, also known as phytohormones are natural compounds that regulate plant growth and development even in very small amounts. They control key processes such as the formation of leaves, stems, flowers and fruits, as well as leaf shedding and fruit ripening. Unlike animals, plants do not have specialized glands for hormone production instead, every plant cell can produce these hormones. These substances are vital because without them plants would not develop properly and would remain undifferentiated tissue. Plant growth regulators (PGRs) encompass both natural hormones and synthetic compounds designed to mimic or influence hormone activity. Some PGRs modify hormone levels, while others alter how plants respond to hormones (Hajam *et al.*, 2017). The five main classical plant hormones are auxins, gibberellins, cytokinins, ethylene and abscisic acid. Beyond these, several newer regulators have been identified including brassinosteroids, salicylic acid, jasmonates, polyamines, nitric oxide and strigolactones. These newer regulators play significant roles, particularly in enhancing fruit crop production when applied externally. Plant Growth Regulators (PGRs) are generally classified into two groups such as growth promoters and growth retardants. Growth promoters support and enhance plant health, growth and development while growth retardants slow plant growth, primarily by inhibiting cell division and reducing stem elongation. Plant growth regulators are extensively used in agriculture, ranging from plant tissue culture to enhancing fruit quality and extending post-harvest shelf life. A key aspect of plant growth regulation is that it is not governed by a single hormone alone but by the interaction among various hormones. For instance, the balance between cytokinin and auxin is critical, higher cytokinin levels promote shoot formation whereas increased auxin levels encourage root development. This interplay illustrates how hormones collaboratively regulate different stages of plant growth and development (Jain, 2013).

2. Recent advances on plant growth promoter and retardants on fruit crops:

2.1. Plant growth promoter and retardants in the regulation of abiotic stress-impacts in fruit crops:

Phytohormones like ethylene, abscisic acid and cytokinin are essential signaling molecules in plant stress responses. Recent studies emphasize their critical role in regulating physiological, molecular and biochemical processes under abiotic stress. Numerous phytohormones, such as jasmonic acid, strigolactones, auxin, salicylic acid and brassinosteroids are vital for developing crops that endure abiotic stress while enhancing growth and productivity, particularly in fruit crops (Ciura and Kruk, 2018).

Plant	**Phytohormone**	**Effect**
Banana	AUX	Regulation of heat stress.
Grape	ABA	Exogenous application of ABA enhances resistance to different abiotic stresses.
Apple	ETHYLENE	The upregulation of the mdnac047 gene enhances salt stress tolerance.
Mango	ABA	Water stress tolerance increases under ABA.
Pear	JA	Phospholipid remodeling promotes alleviation of chilling injury.
Strawberry	SA	Combination with iron nanoparticles reduces the impact of drought stress under in vitro conditions.

(Manzoor *et al*., 2023)

2.2. Plant growth promoters and retardants in canopy management of fruits crops:

Canopy management in fruit trees focuses on optimizing carbon allocation to fruits while sustaining overall tree growth. The canopy includes stems, branches, shoots and leaves. Many orchards become old and less productive due to poor canopy management, resulting in decreased yield and fruit quality, which reduces profitability. This issue can be mitigated through proper training, pruning and the use of growth promoters and inhibitors. Effective canopy management maintains the desired tree structure and improves light interception an important factor since most orchard crops use less than 70% of available sunlight thereby enhancing both yield and fruit quality (Whiley *et al.,* 2013).

PGRS	**Plant Response**
NAA	Regulate plant canopy of litchi.
GA_3	Maximum plant canopy in litchi.
Cytokinin	Increased no. of bud’s active shoot in pruned tea plant.

Brassinosteroids	Flowering initiation and termination, canopy architecture, micropropagation, cell division are all controlled by BRs.
Paclobutrazol	Light pruning with application of paclobutrazol can restrict the canopy growth with enhanced fruit production during the off-season of mango.
Morphactins	It decreases root development throughout the growing season, which may be related to impacts on vegetative growth, blooming, and water and nutrient absorption.
Ethylene	PBZ at 500 ppm, which exhibits the largest growth retarding impact, might be researched further for managing guava tree canopies in high-density planting, considering fruit quality and economic issues.
Chlormequat chloride	However, it was noted that plants had a minimum number of panicles. As a result, these synthetic growth inhibitors will be used to govern litchi's canopy and flowering more effectively.

(Rahul *et al.*, 2023

2.3. Plant growth regulators to improve phytoremediation of contaminated soils:

Soil contamination is a significant global environmental problem and phytoremediation provides an effective approach to removing pollutants from soil, water and air. This process operates through various mechanisms, including phytoextraction, rhizofiltration, phytovolatilization, stabilization, degradation and rhizosphere activity. The efficiency of phytoremediation can be improved by using techniques such as chelating agents, fertilizers, electric currents, beneficial microbes, transgenic plants and plant growth regulators (PGRs). Among these, PGRs like auxins, gibberellins, cytokinins and salicylic acid play a crucial role, although their effectiveness depends on factors like concentration, environmental conditions and plant physiology (Rostami and Azhdarpoor, 2019).

PGRS	**Contaminant (Concentration)**	**Mechanism**
Auxin	Cd (0.05M)	Increasing hemicellulose and stabilizing cadmium in the root.
Auxin	Pb (1mM)	Activating ATPases in the plasma's membrane led to changes in ions transportation through the membrane.
Cytokinin	Ni (15 mg/kg)	Enhancing phytoextraction function by increasing biomass.
Gibberellic acid	Cd (10^{-5}M)	Increasing plant's biomass.

Salicylic acid	Cu (1, 2mM)	Increasing the plant's growth and resistance index under stress.

(Rostami and Azhdarpoor, 2019)

2.4. Light and Plant Growth Regulators on *In Vitro* Proliferation:

Plant tissue culture relies on artificial light for proper growth, influencing both photomorphogenesis and photosynthesis. Light quality, intensity and photoperiod can be controlled to produce desired plant traits. Here we can see that how light characteristics and plant growth regulators affect shoot proliferation *in vitro*, as well as plantlet quality (e.g., shoot length, biomass, and photosynthesis). It also highlights how different light spectra influence endogenous growth regulators. However, results vary widely due to differences in species, environmental conditions and lack of standardized protocols, making it difficult to determine the most effective light conditions.

Explant Type	**Light Spectra**	**Growth Regulators in Medium**	**Results on In Vitro Proliferation**
Vitis vinifera L.	RL BL No LED	BAP at 5 µM	BL = more shoots in the medium containing the lower concentration of manganese sulphate.
Fragaria x ananassa Duch cv. ‘Camarosa’/ Encapsulated shoot tips	Fl (control) RL + BL	Hormone free medium for plantlets development, and 4.9 µM IBA or 6.7 µM BA plus 2.3 µM K for shoots proliferation	RL + BL were most effective for in vitro sprouting of encapsulated strawberry shoot tips.
Malus domestica Genotype MM106 Shoot tips from in vitro cultures	WL, RL, BL, GL, YL, UV-AL, D	8.86 (2 mg L^{-1}) µM BA, 0.53 (0.06 mg L^{-1}) µM Ga3, 0.3 µM (0.1 mg L^{-1}) IBA	GL and WL gave the higher total number of shoots at the end of the fourth culturing cycle.
Musa spp. cv.’Grande naine’AAA)/Meristematic shoot tips	WL, Fl	16.8 µM BAP, 3.8 µM IAA, 1 mg L^{-1} on a temporary immersion system	WL under TIS enhanced shoot proliferation.

(Cavallaro et al., 2022).

2.5. Role of plant growth regulators in improving fruit set, fruit retention, quality and yield of fruit crops:

Plant growth regulators (PGRs) are organic compounds, distinct from nutrients and vitamins that influence plant physiological processes even in minute amounts. They play a vital role in fruit crops by enhancing fruit set, reducing fruit drop and improving both yield and quality. Because fruit trees are high-value crops, even small improvements can substantially increase their economic value. PGRs function by optimizing the internal physiology of developing fruits and correcting physiological disorders, resulting in better overall production (Bons and Kaur, 2020).

Fruit (variety)	PGR (Dose)	Time of spray
Custard apple	GA_3 75 ppm	Twice (1st at flowering stage and 2nd at fruit set stage).
Sapota cv. Kalipatti	NAA (125 ppm)	During flowering and at pea stage.
Papaya cv. Red lady	GA_3 (200 ppm)	30, 45 and 60 days after planting.
Cape gooseberry cv. Aligarh	NAA (15 ppm)	At fruit set.
Mango cv. Himsagar	NAA (40 ppm)	During fruit set stage.
Guava	GA_3 (200 ppm)	Flower anthesis stage.
Pomegranate cv. Bhagwa	2,4- D (15 ppm) GA_3 (50 ppm)	At 15 days interval from fruit set.
Apricot cv. Shadoo	GA_3 (100 ppm)	Twice; after 6 and 10 weeks of full bloom.
Almond cv. Non Pareil	Kinetin 50 ml/L	During bloom at pink bud stage.

(Bons and Kaur, 2020)

2.6. Plant Growth Promoter and retardants in fruit development and maturation:

Plant growth regulators (PGRs) are crucial in fruit development encompassing fruit set, growth and ripening. Fruit set, which occurs after fertilization is primarily regulated by auxin and gibberellins (GAs) through their interactions with specific proteins. Fruit growth involves both cell division and expansion, processes mainly driven by auxin and supported by GAs and other hormones. During maturation, auxin and GA levels decline, while abscisic acid (ABA) and ethylene levels rise. In the ripening phase, ethylene predominantly controls climacteric fruits, whereas ABA plays a more significant role in non-climacteric fruits (Fenn and Giovannoni, 2021).

Crops	PGRS	Mechanism
Pear (*Pyrus communis*)	2,4-D	Stimulate the expression of GA20ox and GA3ox to increase GA biosynthesis and induce parthenocarpy fruiting.
Strawberry	ABA	As ripening proceeds, ABA levels progressively increase as FvNCED1 and FvABA2 are upregulated, and its accumulation peaks at the 'fully red' stage.
Banana (*Musa* spp.)	Ethylene	Upregulates expression of a calcium-dependent protein kinase, MaCDPK7. The induction of MaCDPK7 not only precedes induction of ACS/ACO and a subsequent increase in respiration typical of climacteric ripening.
Bilberry (*Vaccinium myrtillus*).	ABA	Upregulates neoxanthin synthase (VmNSY) and anthocyanidin synthase (VmANS) to increase anthocyanin accumulation.

(Fenn and Giovannoni, 2021)

2.7. Post Harvest Treatment through Plant Growth Promoter and Retardants:

Plant growth regulators (PGRs) are used postharvest to extend shelf life, delay senescence, control ripening and reduce disease development. Their

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effectiveness depends on factors like concentration, environmental conditions and plant sensitivity (Wang *et al*., 2014).

Crops	**PGRS**	**Effect**
Mango	2,4-D	Reduced chilling injury through an increase of ABA and GA levels and an augmentation of antioxidant defenses.
Chilean strawberry	NAA	postharvest treatment delays fruit ripening without effect on firmness.
Orange	GA3	Induces antioxidant defenses which delays ripening and maintains green peel color longer in orange).
Persimmon	6-BA and GA	Mixture of applied during culture improved quality during storage and enhances tolerance to Alternaria black spot.
Banana	CPPU and GA	Mixture can also delay ripening and increase fungal tolerance.
kiwifruits	CPPU	Applied during fruit development improves cold storage.
Mango	Abscisic acid	Plays a major role in fruit ripening where ABA controls, via ethylene production, cell wall catabolism leading to a modification of texture and to a diminution of shelf-life.

(Wang *et al*., 2014)

3. Conclusion:

Plant growth regulators (PGRs) are essential tools in modern fruit crop management due to their diverse roles in plant physiology. Their application boosts productivity by improving fruit set, minimizing fruit drop and enhancing both yield and quality. Additionally, PGRs contribute to managing abiotic stress, optimizing canopy structure and supporting sustainable practices like phytoremediation and tissue culture. During fruit development, the coordinated interaction of hormones governs successful growth and ripening while postharvest use of PGRs helps maintain quality and prolong storage life. The effectiveness of PGRs depends on factors such as correct concentration, timing, environmental conditions and crop specificity. Thus, precise and well managed application is crucial to maximize their benefits. Future research should aim to standardize application protocols and deepen understanding of hormonal interactions to further improve their efficiency in fruit crop production systems.

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Advances in Maize-Based Bioethanol Production: Conversion Pathways, Feedstock Dynamics and

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Rising dependence on fossil fuels and mounting pressure to curb greenhouse gas emissions have intensified global interest in bioethanol as a renewable liquid fuel. While first-generation feedstocks still dominate world production, with the United States relying on maize grain and Brazil on sugarcane, countries such as India are shifting toward grain-based feedstocks to meet ambitious ethanol-blending targets. This article reviews the biochemical basis of bioethanol conversion, tracing the pathway from complex carbohydrates to fermentable sugars and, ultimately, to fuel-grade ethanol. It evaluates maize as a feedstock, highlighting its C4 photosynthetic efficiency and starch composition, particularly the amylose-to-amylopectin ratio, as key determinants of conversion performance. The discussion extends to the dry-grind processing cascade used in commercial maize biorefineries and to emerging innovations, including cold starch hydrolysis, in-planta enzyme expression and 1.5-generation biorefinery integration, each of which reduces energy input or expands substrate utilization without requiring additional cultivated land. Collectively, these advances position maize as a scalable, energy-efficient feedstock for expanding bioenergy production, offering researchers, policy planners and industry stakeholders a practical basis for optimizing maize-based ethanol systems.

1.Introduction

Global dependence on fossil fuels drives significant greenhouse gas emissions while accelerating the depletion of finite petroleum reserves. Bioethanol offers a viable liquid fuel alternative that can be integrated into existing internal combustion engines and fuel distribution systems with minimal modification (Balat, 2008). On a global scale, bioethanol production is dominated by first-generation feedstocks (McAloon *et al*., 2000; Chiong *et al*., 2018). The United States relies primarily on maize grain, while Brazil utilizes sugarcane (Madhurjya *et al*., 2024). Other regions, including the European Union and China, utilize a mixture of maize and wheat. In countries such as India, escalating national blending targets have driven a strategic shift from traditional sugarcane molasses toward grain-based feedstocks, highlighting maize as a critical commodity for bioenergy security (Saini *et al*., 2023).

2. Fundamental Principles of Bioethanol Conversion

Bioethanol synthesis relies on the enzymatic or chemical breakdown of complex carbohydrates into fermentable monosaccharides, followed by microbial fermentation (Demirbas, 2007). Carbohydrate sources generally fall into three structural categories:

1. **Free Sugars:** Sucrose found directly in sugarcane and sugar beet.
2. **Storage Starch:** α-linked glucose polymers found in cereal grains such as maize and wheat.
3. **Lignocellulosic Matrix:** β-linked cellulose and hemicellulose complexed with structural lignin within plant cell walls.

In standard biochemical pathways, the feedstock undergoes pretreatment to expose the polysaccharide chains (Sahoo, 2016). Enzymatic hydrolysis breaks these polymers down into monosaccharides (primarily D-glucose) (Haq *et al*., 2016). *Saccharomyces cerevisiae* or specialized bacterial

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strains subsequently ferment these hexose sugars under anaerobic conditions (Cardona and Sánchez, 2007).

$C_6H_{12}O_6 \rightarrow 2\ C_2H_5OH + 2\ CO_2$

The resulting dilute ethanol solution is concentrated via multi-column distillation and dehydration to meet fuel-grade standards (Cardona and Sánchez, 2007).

3. Comparative Evaluation of Maize as a Feedstock

3.1 Physiological and Biochemical Advantages

Maize possesses a C_4 photosynthetic pathway, enabling high biomass accumulation and efficient water and nitrogen utilization relative to C_3 cereals. Starch constitutes 70% to 75% of the dry weight of the maize kernel (Dhugga *et al.*, 2007). Starch exists in two primary polymers:

- **Amylose:** A linear polymer linked by α-1,4-glycosidic bonds.
- **Amylopectin:** A highly branched polymer linked by α-1,4- and α-1,6-glycosidic bonds.

The open, branched architecture of amylopectin increases accessibility for hydrolytic enzymes compared to densely packed amylose. Consequently, maize genotypes exhibiting higher amylopectin-to-amylose ratios yield higher sugar conversion rates and superior ethanol recovery.

3.2 Cross-Feedstock Benchmarking

Feature	Maize Grain	Sugarcane Juice	Lignocellulosic Residues
Primary Substrate	Starch (α-glucan)	Sucrose (Disaccharide)	Cellulose & Hemicellulose
Processing Complexity	Moderate (Requires liquefaction & saccharification)	Low (Direct fermentation of juice)	High (Severe pretreatment & recalcitrance)
Geographic Adaptability	Broad (Temperate, Subtropical, Tropical)	Restricted (Tropical/Subtropical)	Broad (Global residue availability)
Key Technical Bottlenecks	Energy input for thermal gelatinization	Perishability & seasonal harvesting	High enzyme cost & lignification

4. Dry-Grind Processing Cascade for Maize

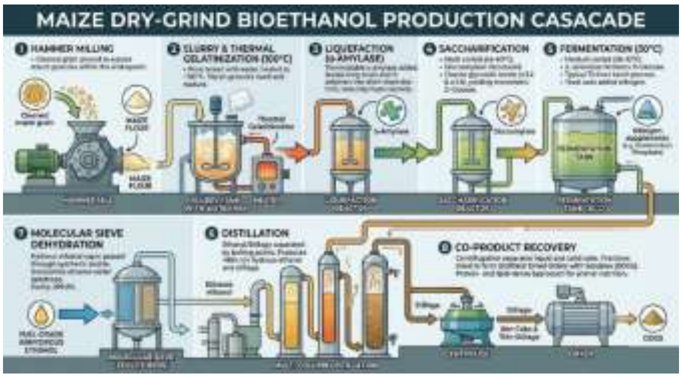

Fig. 1: Dry-grind processing cascade for maize-based bioethanol production.

5. Technical Innovations in Maize Biorefineries

5.1 Cold Starch Hydrolysis

Conventional liquefaction requires significant thermal energy to cook mash near 100°C. Cold Starch Hydrolysis employs Granular Starch Hydrolysis Enzymes (GSHE) capable of digesting native, ungelatinized starch granules at ambient temperatures (30–32°C). This eliminates high-temperature cooking, reducing facility thermal energy requirements by an estimated 30–40% while preventing Maillard reaction losses of fermentable sugars.

5.2 In-Planta Expression of Processing Enzymes

Transgenic technology allows processing enzymes to be expressed directly within the seed endosperm during grain development (e.g., Syngenta Enogen). Upon milling and hydration, the grain releases built-in thermostable α-amylase. This self-liquefying trait reduces exogenous enzyme requirements and lowers initial mash viscosity during processing.

5.3 1.5-Generation Biorefinery Integration

The pericarp of the maize kernel contains cellulosic and hemicellulosic fractions that traditionally pass through unfermented into the DDGS fraction. In 1.5-generation systems, mild chemical or hydrothermal pretreatments (e.g., liquid hot water or alkaline extrusion) are integrated directly into the dry-grind facility to hydrolyze pericarp fiber into hexose and pentose sugars. Recombinant yeast strains capable of xylose and glucose co-fermentation increase ethanol yields per unit of grain without expanding cultivated land area.

6. Conclusions

Maize remains a cornerstone feedstock for global bioethanol production due to its high starch density, favorable amylopectin architecture, and established dry-grind processing infrastructure. Innovations such as non-thermal cold starch hydrolysis, *in-planta* enzyme expression, and 1.5-generation fiber co-fermentation address the energy inputs and substrate limitations of conventional processing. When paired with high-yielding, starch-rich hybrids and optimized processing parameters (e.g., 15% substrate loading), maize-based bioethanol provides a scalable pathway for expanding bioenergy production.

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Strategies for Sustainable, Resilient and Resource-Efficient Vegetable Production

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Vegetables are an essential component of human diet and an important source of vitamins, minerals, dietary fibre, antioxidants and other bioactive compounds. India is one of the major vegetable-producing countries in the world with a wide range of crops including tomato, chilli, brinjal, okra, cabbage, cauliflower, cucurbits, onion and leafy vegetables. However, vegetable production is increase being challenged by changing climatic conditions.

Rising temperatures, irregular rainfall, prolonged dry periods, heat waves, heavy rainfall, hailstorms, frost and changes in pest and disease behavior also adversely affect vegetable growth, yield and quality. Since most vegetable crops are relatively short-duration and input-intensive even short periods of climatic stress during flowering, fruit setting or crop establishment can result in significant economic losses.

In this situation, Climate-Smart Agriculture (CSA) provides an important approach for making vegetable production more productive, resilient and sustainable. Climate-smart vegetable production aims to improve productivity, enhance the ability of crops and farmers to cope up with climate variability, and use of natural resources more efficiently.

WHY CLIMATE-SMART VEGETABLE PRODUCTION IS NEEDED

Climate change can affect almost every stage of vegetable crop production. High temperature may reduce pollen viability, flowering and fruit setting, while excessive rainfall can cause waterlogging, root diseases and nutrient losses. Therefore, climate-smart production focus on productivity, resilience and efficient resource use.

Major Climate-Smart Strategies

1. Selection of Climate-Resilient Varieties

Farmers should select varieties and hybrids adapted to local climatic conditions and showing tolerance to heat, drought, excess moisture and important pests and diseases. Heat-tolerant and disease-resistant varieties can reduce crop losses and dependence on repeated chemical plant protection.

2. Adjustment of Sowing and Transplanting Time

Sowing and transplanting dates should be managed according to local temperature and rainfall conditions. Sensitive crops should preferably be established so that critical flowering and fruit-setting stages do not coincide with periods of extreme heat.

3. Drip Irrigation and Efficient Water Management

Water scarcity is a major constraint to vegetable production. Drip irrigation supplies water directly to the root zone and reduces evaporation and unnecessary water loss. Fertigation improves water and nutrient-use efficiency. Rainwater harvesting, farm ponds and recharge structures can further strengthen water security.

ISSN: 3049-2289

4. Mulching for Moisture and Temperature Management

Mulching is a simple and effective climate-smart practice. Organic materials such as straw, dry grass, leaves and crop residues can be used as mulch, while plastic mulch is also widely used in commercial vegetable production. Mulching conserves soil moisture, moderates soil temperature, suppresses weeds and reduces soil erosion.

5. Protected Cultivation

Polyhouses, greenhouses, shade-net houses and low tunnels can protect crops from extreme temperature, strong winds, hail and other adverse weather events. These structures provide better control over temperature, humidity, irrigation and light and can improve productivity and produce quality.

6. Soil Health Management

Healthy soil is fundamental to climate-resilient crop production. Application of farmyard manure, compost, vermi-compost, green manure and suitable crop residues can improve soil organic matter, structure and water-holding capacity. Regular soil testing should be encouraged to determine nutrient requirements. Improved soil health helps crop tolerate periods of water stress and supports better root development and nutrient availability.

7. Integrated Nutrient Management

Integrated Nutrient Management (INM) involves the balanced use of organic manures, bio-fertilizers and mineral fertilizers according to crop requirement. Excessive and unbalanced fertilizer use may reduce nutrient-use efficiency and increase production costs. Balanced nutrient management can improve plant growth, yield and quality while reducing nutrient losses to the environment. Foliar nutrition and fertigation can also be used where appropriate during critical crop-growth stages.

8. Integrated Pest and Disease Management

Climate variability can influence pest multiplication and disease development. Integrated Pest Management (IPM) should therefore be an important component of climate-smart vegetable production.

- Use healthy and disease-free planting material.
- Prefer resistant or tolerant varieties.
- Practice crop rotation and field sanitation.
- Use pheromone, yellow and blue sticky traps.
- Conserve or introduce biological control agents.
- Use neem-based products where appropriate.
- Apply recommended pesticides only when needed and according to label directions.

An integrated approach reduces unnecessary pesticide use, production costs and environmental risks.

9. Crop Diversification and Crop Rotation

Dependence on a single vegetable crop can increase economic and climatic risk. Crop diversification distributes risk among different crops and production periods. Intercropping and crop rotation improve resource utilization and help in breaking pest and disease cycles. Including crops with different durations and climatic requirements can make farming systems more resilient to unpredictable weather.

ISSN: 3049-2289

10. Weather-Based Agro-Advisory Services

Weather information can play a significant role in climate-smart farming. Farmers can use forecasts to make timely decisions regarding irrigation, fertilizer application, pesticide spraying and harvesting. Mobile-based agricultural advisories, automatic weather stations and digital platforms can help farmers in taking timely measures for to heat waves, heavy rainfall, frost and other weather-related risks.

11. Precision Horticulture and Smart Technologies

Modern technologies are creating new opportunities for climate-smart vegetable production. Precision horticulture uses sensors, remote sensing, drones, GPS and data-based decision-making to improve crop management. Sensors can monitor soil moisture, temperature and humidity, while drones and remote sensing can help identify crop stress and variations in crop growth. In protected cultivation, automated irrigation, fertigation and climate-control systems can improve input-use efficiency and reduce labour requirements.

12. Carbon and Energy Management

Climate-smart agriculture also focusses on reducing greenhouse gas emissions. Crop residues should preferably be composted, incorporated into the soil or used as mulch instead of being burned. Solar-powered irrigation systems, energy-efficient pumps and improved protected cultivation technologies can reduce dependence on fossil fuels. Efficient use of water, fertilizers and energy can simultaneously reduce production costs and the environmental footprint of vegetable farming.

A Practical Climate-Smart Model for Vegetable Growers

A practical climate-smart vegetable production model for small and medium farmers can integrate:

Quality planting material + climate-resilient varieties + drip irrigation + mulching + balanced nutrition + IPM + crop diversification + protected cultivation + weather-based advisories.

Farmers can adopt these technologies gradually according to their resources and local climatic conditions. Even simple interventions such as mulching, improved irrigation scheduling, quality seed and weather-based decision-making can significantly improve resilience.

Benefits of Climate-Smart Vegetable Production

- Improved crop establishment and productivity
- Better water-use efficiency
- Reduced production losses due to climatic stresses
- Improved soil health
- Reduced dependence on pesticides
- Efficient use of fertilizers
- Better quality and marketable produce
- Lower production risks
- Improved farm profitability
- Greater sustainability of vegetable production systems

Future Prospects

The future of vegetable production will increasingly depend on the ability of farmers to adapt to climate variability. Integration of traditional knowledge with modern technologies can provide practical solutions for different agro-climatic regions.

Agricultural universities, research institutions, extension agencies, government departments and private organizations should work together to promote climate-resilient varieties, water-saving technologies, protected cultivation, precision horticulture and digital agro-advisory services. Special attention should also be given to small and marginal farmers by making climate-smart technologies affordable, accessible and locally appropriate.

ISSN: 3049-2289

Conclusion

Climate change is emerging as a major challenge for sustainable vegetable production. However, appropriate planning and adoption of climate-smart technologies can significantly reduce climate-related risks.

The use of climate-resilient varieties, adjusted planting dates, drip irrigation, mulching, protected cultivation, soil-health management, integrated nutrient management, integrated pest management, crop diversification and precision horticulture can make vegetable production more resilient, productive and resource-efficient.

Climate-smart vegetable production is therefore not simply a response to climate change; it is an opportunity to develop a more profitable, sustainable and resilient horticultural production system. Strengthening farmer awareness, technical knowledge and access to appropriate technologies will be essential for ensuring future vegetable production, farmer income and food and nutritional security

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Toxic Plants as a Threat to Livestock Fertility: Reproductive Effects and Management Strategies

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Toxic plants represent a major concern in livestock production because exposure can adversely affect reproductive performance as well as general animal health. Many poisonous plant species contain biologically active substances capable of altering endocrine function, reducing fertility, causing developmental defects, or increasing the risk of abortion. This review focuses on poisonous plants associated with reproductive disorders in livestock, with particular attention to species such as Astragalus, Lupinus, and Veratrum californicum. It considers their principal toxic compounds and the reproductive effects reported in cattle, sheep, goats, and other domestic animals. The economic consequences of poor reproductive performance are also considered, including reduced productivity and increased management and veterinary costs. Strategies for reducing exposure include effective pasture management, identification and removal or avoidance of poisonous plants, appropriate treatment following exposure, and regular monitoring of grazing livestock. A clear understanding of plant-induced reproductive toxicity is essential for maintaining herd health, reducing financial losses, and supporting sustainable livestock production.

Introduction

Poisonous plants remain an important problem in livestock agriculture because they can negatively influence animal health, productivity, and farm profitability. A wide range of toxic plant species occurs in pastures, rangelands, and forage resources, and some may also contaminate feed products. Depending on the plant species, amount consumed, and duration of exposure, poisoning may result in gastrointestinal disturbances, neurological abnormalities, reproductive disorders, or death. The risk is particularly high in extensive grazing systems, where livestock may consume toxic vegetation when preferred forage is limited. Inadequate pasture management, insufficient knowledge of poisonous plants, and seasonal shortages of nutritious forage can further increase the likelihood of exposure.

The financial consequences of plant poisoning can be considerable. Losses may arise from animal mortality, veterinary treatment, reduced productivity, reproductive failure, and the additional expense of providing alternative feed or supportive care. Even when poisoning does not result in death, chronic exposure to toxic substances can reduce animal performance and compromise the long-term productivity of a herd or flock.

Environmental contaminants can create additional risks. Plants may accumulate heavy metals from contaminated soils or irrigation sources, while pesticide residues can enter the plant-animal production system through agricultural practices. Following ingestion, these contaminants may interfere with normal physiological and metabolic processes and can contribute to impaired growth, production, and reproductive performance. Appropriate environmental monitoring, treatment, and management practices are therefore important components of livestock health programs.

Reproductive toxicity is of particular concern because certain poisonous plants contain compounds that can interfere with endocrine regulation and reproductive function. Exposure to substances such as pyrrolizidine alkaloids and excessive nitrates has been associated with impaired fertility, pregnancy loss, fetal abnormalities, and other reproductive problems under particular exposure conditions. The severity of these effects depends on factors including the plant species, toxic compound, dose, duration of exposure, animal species, and physiological stage of the animal.

Several poisonous plants have been identified as potential causes of reproductive disorders in livestock. Locoweeds, particularly Astragalus mollissimus, A. lentiginosus, and Oxytropis sericea, contain the indolizidine alkaloid swainsonine. Exposure to these plants can impair libido and disrupt both spermatogenesis and oogenesis. In females, poisoning may alter estrous behaviour, prolong or otherwise disturb the estrous cycle, and interfere with ovarian function, including the development of cystic ovarian conditions. Reproductive consequences may include reduced conception rates, poor embryonic and fetal viability, and impaired maternal behaviour. In pregnant animals, hydrops amnii, placental resorption, abortion, fetal myocardial dysfunction, and congenital abnormalities, including undersized calves and phocomelia-like limb abnormalities in lambs, have been reported.

Several range and pasture plants, including Gutierrezia sarothrae (broom snakeweed, perennial snakeweed, or turpentine weed), G. microcephala (threadleaf broomweed), Chrysothamnus nauseosum, and sneezeweed (Helenium hoopesii), contain combinations of saponins, selenium, alkaloids, terpenes, and flavonols that can adversely affect reproduction. Exposure has been associated particularly with abortion in cattle and the birth of weak or undersized offspring. Tall fescue (Festuca arundinacea), when infected with the endophytic fungus Neotyphodium coenophialum, exert anti-prolactin effects. Consumption can result in prolonged gestation, abortion, placental thickening, agalactia, dystocia, and reduced conception rates, with reproductive problems documented in both cattle and mares.

Chronic selenium poisoning can also interfere with reproductive function. Excess selenium exposure has been associated with abnormal sperm maturation and reduced sperm motility in rams, while affected ewes may experience early embryonic death or failure to establish a pregnancy. Cottonseed, because of its content of the polyphenolic compound gossypol, can adversely affect male reproductive development, including altered testicular development in rams and bulls. In contrast, subterranean clover contains phytoestrogens such as genistein and formononetin, which possess estrogenic activity and have been associated with infertility and uterine prolapse in ewes.

Lupines contain quinolizidine alkaloids such as anagyrine and ammodendrine. Consumption by pregnant animals can produce teratogenic effects and is associated with the condition commonly referred to as crooked calf disease. A related group of plants containing piperidine alkaloids, including poison hemlock (Conium maculatum), wild tree tobacco (Nicotiana glauca), tobacco stalks (Nicotiana tabacum), and Lupinus formosus, can cause severe developmental abnormalities. Exposure during pregnancy may result in multiple congenital skeletal contractures, dystocia, and a range of birth defects in cattle and swine, including angular limb deformities, arthrogryposis, scoliosis, torticollis, and cleft palate.

Plants such as sorghum, Sudan grass, corn, lima beans, cherry, apple, peach, and apricot can contain cyanogenic glycosides, including amygdalin, prunacin, linamarin, lotaustralin, dhurrin, and taxiphyllin. When these compounds release cyanide after ingestion, reproductive consequences can include skeletal contracture defects in the offspring of pregnant animals. Such abnormalities have been described particularly in pigs and horses, including the condition known as contracted foal syndrome. Rosary pea (Abrus precatorius) contains the highly toxic protein abrin, and chronic exposure has been associated with placental expulsion and abortion in cattle. Similarly, wild black cherry (Prunus serotina) contains cyanogenic glycosides such as amygdalin, which can release prussic acid and has been associated with contracture deformities in piglets.

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Jimson weed contains tropane alkaloids, principally atropine, hyoscyamine, and scopolamine. Maternal exposure can interfere with fetal development and has been associated with skeletal deformities in pigs. Veratrum californicum, commonly known as false hellebore or corn lily, contains teratogenic steroidal alkaloids, including cyclopamine, jervine, and muldamine. In pregnant ewes, ingestion can cause severe craniofacial abnormalities, including cyclopia accompanied by anencephaly, a characteristic condition commonly known as monkey-faced lamb disease.

Lantana camara contains the toxic lantadenes, particularly lantadene A and lantadene B, which can interfere with several aspects of female reproductive function. Exposure has been associated with altered estrous behaviour, changes in estrous cycle length, impaired ovarian function, reduced conception, and decreased embryonic and fetal viability. Bracken fern (Pteridium aquilinum var. pubescens) contains thiaminase-related antinutritional factors and ptaquiloside. Its consumption can adversely affect estrous behaviour and ovarian function, thereby contributing to reproductive disturbances.

Several species of conifers have also been implicated in reproductive toxicity. These include ponderosa pine (Pinus ponderosa), lodgepole pine (Pinus contorta), Monterey cypress (Cupressus macrocarpa), Jeffrey pine (Pinus jefferyi), Rocky Mountain juniper (Juniperus scopulorum), common juniper (J. communis), Utah juniper (J. osteosperma), and western juniper (J. occidentalis). These plants contain isocupressic acid, which is metabolized into compounds such as agathic acid, imbricatoloic acid, dihydroagathic acid, and tetrahydroagathic acid. These substances can interfere with fetal and placental blood flow, resulting in fetal hypoxia and physiological stress and potentially leading to abortion in cattle. Affected animals may also give birth to dead or premature calves and may develop retained placenta and subsequent uterine infections.

Nitrate-accumulating crops and plants represent another important source of reproductive toxicity. Crops that may accumulate excessive nitrate include oats, beets, rape, turnips, soybeans, barley, flax, alfalfa, millet, rye, sorghum, Sudan grass, Johnson grass, wheat, and corn. Numerous weeds can also accumulate nitrates, including ragweed, pigweed, wild oats, musk thistle, lambsquarter, Canadian thistle, field bindweed, barnyard grass, cudweeds, sunflowers, fireweed, skeleton plant, cheeseweed, sweet clover, smartweed, dock, Russian thistle, milk thistle, nightshades, and goldeneye. Excessive intake of nitrates and nitrites can compromise reproductive performance and, particularly when exposure is widespread within a herd, may result in an abortion storm.

Treatment

1. Ample fluid therapy to dilute toxins, Liver supplements and electrolytes
2. Administration of saline purgatives and urine alkalizers for excretion of toxins
3. Activated charcoal (2.5 kg in 20 liters of electrolytic solution) orally in lantana poisoning
4. Intravenous administration of 1 ml of 20% sodium nitrate and 3 ml of 20% sodium thiosulfate, given at a dose rate of 4 ml/45 kg Bwt. In sheep, sodium thiosulfate @ 660 mg/ kg along with sodium nitrite @ 6.6 mg/ kg given in cyanogenic plant poisoning
5. In case of Nitrate poisoning, intravenous methylene blue administration 8 mg/kg Bwt. repeated every 2 hours in cattle
6. Administration of anti bloat drugs orally or directly into rumen
7. Oral administration of purgatives such as Epsom's salts, and kaolin (fine white clay powder) in water to remove toxins from the gut

8. Thiamine inj. in case of Bracken fern poisoning
9. Feeding animals with Tulsi, Fenugreek seeds solution to detoxify poisonous agent
10. Providing garlic in small quantities orally to reduce the problem of stomach ache and diarrhea

Prevention

- ❖ Aversive conditioning (Training livestock to avoid eating toxic plants)
- ❖ Stall feeding
- ❖ Providing contaminants free clean potable water
- ❖ Regular testing of animal feed and water
- ❖ Precautions while cutting fodder to avoid toxic plants, weeds, succulent immature grass for feeding animals
- ❖ Avoiding mouldy grains, hay and forage to the animals

Conclusion

The impact of toxic plants on livestock reproduction is a complex and multifaceted issue that requires a holistic and collaborative approach. Continued research, comprehensive understanding of the underlying mechanisms, development of innovative solutions, and the adoption of sustainable agricultural practices can play a crucial role in protecting the health and productivity of the animal, ensuring the sustainability of the country's agricultural sector.

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Current Robotic Approaches for Precision Weed Management

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The purpose of this article is to provide insight into current robotic approaches for weed management. It highlights the major developments that have emerged in recent years to support widespread adoption, while also considering the constraints, future innovations and potential applications.

Weeds continue to cause significant yield and economic losses due to competition with crops. Additionally, labour shortages, herbicide resistance, and environmental pollution present further challenges, making effective weed management increasingly difficult.

To counter these challenges, various weed-control methodologies have emerged. Precision weed-control technologies (PWC), including robots and unmanned aerial vehicles (UAVs), offer innovative and effective solutions.

Introduction

Weeds are invasive plants that occupy farmland and deprive crops of vital resources like light, nutrients, and space. Failure to control them leads to restricted crop growth, lower production, and financial losses for farmers [6]. In traditional weed management, the entire field is usually sprayed uniformly with one standard herbicide dose, treating soil, crops, and weeds alike. Today's smart farming and agricultural management techniques depend on accurate, detailed insights into field conditions. The use of robots and UAVs in PWC allows for highly accurate identification and treatment of weedy patches, resulting in optimized use of resources, less herbicide waste, and significant cost savings [3]. Techniques for farm monitoring involve aerial vehicles like UAVs, which can inspect large tracts of land in a much shorter time compared to ground machines. At present, weed-control robots rely on real-time image detection, as timely weed identification and management are crucial.

Typical site-specific weed management (SSWM) involves four key stages:

1. **Data Acquisition**
2. **Weed Identification**
3. **Weed Control**
4. **Performance Assessment**

Execution Platform in Weed Control

Precision weed control (PWC), powered by advanced tools like robots and UAVs, mainly uses two methods to apply herbicides at variable rates. The first is the map-based VRA, which uses digital field maps to decide how much herbicide to spray; this method is commonly used with UAVs. The second is the sensor-based VRA, which uses real-time sensor data to adjust herbicide rates on the spot based on the field's specific needs.

Weed Control Through Robots

Self-operating robots with built-in sensors, imaging systems, and mechanical devices are being deployed to detect and remove weeds. They serve as an advanced alternative to conventional hand weeding or herbicide use. The key components of robotic

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weed control systems are sensors, data analysis, mechanical tools, and autonomous navigation.

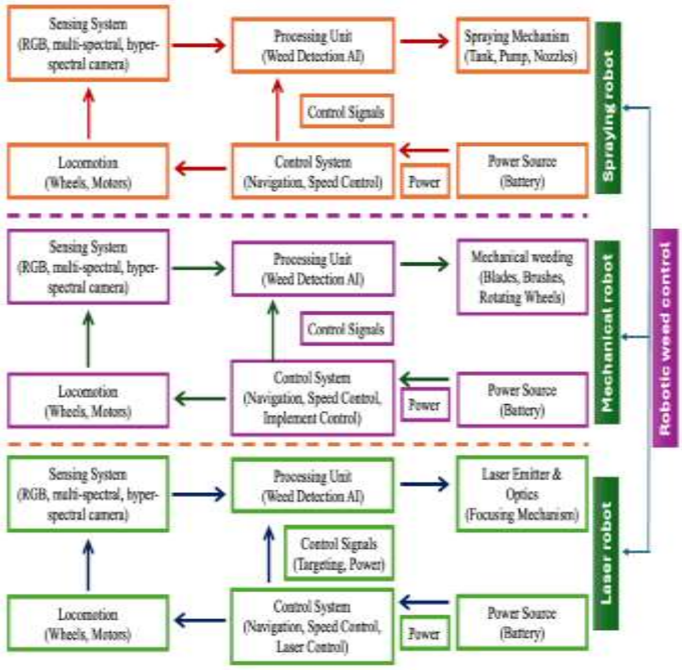

Fig: Different types of weeding robots used in agriculture and their block diagrams illustrating the key components and functionalities.

Spraying Robots

Have spraying mechanisms, such as nozzles, that accurately dispense herbicide onto weeds. This helps reduce usage, increase efficiency, and minimise drift and environmental harm.

Mechanical Weeding Robots

They are equipped with Implements or tools such as blades, brushes, or rotating wheels that physically remove weeds from soil.

Laser Weeding Robots

Precise targeting and elimination of weeds through a laser beam. High-density energy laser beams are used to target spots, thereby heating the plant tissue or stems of the weed and ultimately rupturing the cells, leading to the death of the weed plant.

Fig: Spraying robots (a)LadyBird (b) RIPPA; Mechanical weeding robots (c) Dino (d) ORIO.

Currently Emerging Weeding Robots

Agriculture robots or Agribots are currently being taken up in Agriculture. It will for sure change the face of farming in the coming years because of exponential growth in its research and development [7].

Table: The weeding robots proposed in the past few years.

Name	**Country**	**Scope**	**Year**	**Methods**	**Sensor**
Tertill [8]	-	Gardens	2017	Mechanical	Capacitive sensors
EcoRobotix[9]	Switzerland	-	2015	Electricity	RGB camera
LaserWeeder[10]	America	-	2021	Laser	Camera
BoniRob [11]	Germany	Sugar beet	2015	Mechanical	RGB, NIR cameras, and ultrasonic sensor

ISSN: 3049-2289

AVO[12]	Switzerland	Bean, cotton, rapeseeds	2020	Chemical	RGB camera
Ladybird[13]	Australia	Lettuce, cauliflower and broccoli	2015	Chemical	Hyperspectral and thermal cameras
AgBotII[14]	Australia	Thistle, feather top rhodes grass and wild oats	2015	Mechanical	RGB camera
TerraSentia[15]	America	Maize, soybean	2018	-	RGB camera
weed robot 1[16]	Japan	Paddy field	2018	Mechanical	-
weed robot 2	Japan	Paddy field	2018	Mechanical	

Tertill™

Commercialised by Franklin Robotics, designed for home gardeners for weeding, operating with a solar-powered system. It works just like a home vacuum cleaner, using its sensors to avoid walls and crops during its operation. It has a capacitive sensor at the bottom for detecting small weeds. It's extremely versatile, moving in all four directions with its four-chambered wheels, making it a unique fit for rough terrain.


Tertill


EcoRobotix


LaserWeeder


BoniRob


AVO


Ladybird


AgBotII


TerraSentia


Weed robot 1

EcoRobotix

It's an Autonomous robot controlled remotely, designed to identify and remove weeds. An ultra-high-precision sprayer is used for ultra-targeted application of herbicides, ensuring minimal product use, reducing inputs up to 95%. Three steps are involved: sense, decide, and act. High-speed and high-resolution cameras capture and detect a diverse array of crops and weeds in real time for analysis. Sub-centimetre plant detection recognises over 50 weed species. Uses ultra-high precision spraying of a 6x6 cm pattern with millisecond timing and accuracy.

LaserWeeder

Launched by Carbon Robotics™ in February of 2022, an autonomous laser weeder using deep learning computer-based vision identifies, targets and eliminates while driving autonomously over the crop rows. It is owned and operated in North America, Europe and Australia by more than 100 growers. A tractor of minimum horsepower 175 hp is required for its operation.

BoniRob

It is a flexible vehicle with 4 wheels steered separately, with moving arms; it can adapt its track width from 0.75m to 2m and its chassis clearance from 0.4m to 0.8m. It's controlled by a number of dedicated control units. They are connected with Ethernet and work using TCP/IP.

System technology: PC, Microcontroller, Embedded systems, Ethernet, Wireless-LAN, Middleware-based communication structure

Navigation sensor technology: 2D-Laserscanner, 3D-Laserscanner, Acceleration sensor, Gyroscope, RTK-GPS

Phenotyping sensor technology: Spectral Imaging, 3D time-of-flight camera, Light curtain, Laser distance sensor

AVO

A solar-powered rechargeable battery100% autonomous machine deploying high precision using 90% less herbicides for ecological and economical weeding pf row crops, meadows, and intercropping cultures. User fits information about the field boundary and crop line in the user interface. The system generates a navigation path for a high degree of precision, combining GPS RTK positioning and visual navigation. A four-wheel drive system manoeuvred independently to help in clearing obstacles and slopes in the farm field. Standard speed 0.6 ha/hr can be achieved, and it can also be operated at night. It can treat up to 10 ha/day, including night operation. By the use of a multi-camera vision system, it detects weeds and sprays on them with its 52 equidistant nozzles, having a height-adjustable spraying ramp.

The user can control and monitor the AVO robots through the ecoRobotix^{TM} mobile app for their operations. Technical specifications include a GPS antenna, photovoltaic panels, front control panel, row tracking camera, access hatch for herbicide mixture reservoir refill, tool system with nozzle spray bar, exchangeable batteries, and 4WD system.

Ladybird

An autonomous field robot, inspired by Coccinellidae or the ladybird, solar or battery powered, having numerous sensing systems including hyperspectral, thermal, stereovision, panoramic vision with probe, LiDAR and GPS, helping in crop assessment. It is designed by the Australian Centre for Field Robots (ACFR), The University of Sydney in 2014.

Moves along the field with independently steerable wheels installed on each corner of the chassis. Omnidirectional capabilities allow it to manoeuvre in confined spaces. It's an all-electric vehicle with lithium-iron phosphate batteries. Solar panels are installed to charge the system. On a clear day, Lady Bird can operate at low speed with power loss.

Localisation is administered via a NovAtel Synchronised Position Attitude Navigation (SPAN), global positioning and inertial navigation system (GPS/INS). Real-time kinematic (RTK) corrections are transferred to the system via a 4G cellular connection.

AgBotII

The AgBotII is a small, lightweight robot platform, designed to be a modular, ready-to-assemble kit. It has a single downward-facing camera along with a lighting module for weed detection and classification. Farmer controls AgBotII with a virtual global interface for autonomous control and a radio-frequency remote for manual control as and when required.

Comprises seven major vehicle assemblies: the modular side units, implement unit, battery boxes, swing arms, drive units, caster assemblies, and external covers. AgBotII has Intel i7 computers with two quad-core, one for navigation and the other for perception. The perception computer has NVIDIA GTX 960 graphics for parallel processing. Software

ISSN: 3049-2289

is built upon the Robot Operating System (ROS) framework and split across two computers. The first computer handles navigation and core functions. The second computer is a more powerful computer where perception software runs.

TerraSentia

TerraSentia is designed to automate the measurement of plant traits for efficient phenotyping as an alternative to manual measurements. Rugged, autonomous, and simple robot created for unprecedented under-canopy field data and trait analysis. Tightly integrated data collection system consisting of 4 high-definition RGB cameras, rich 3D datasets, perception, highly accurate positioning, even with degraded GPS. Has powerful onboard computers and long-range connections. Has a powerful drive capable of handling clay soils and rough terrain. Minimum 3 hours battery life due to optimised data transfer at low bandwidth. It can scan 10 plants in one second, all day long, recording 5+ traits simultaneously.

Weed robot 1

The proposed weeding robot consists of a camera-based sensing system that, via image processing, helps it turn around at the end of a row of rice seedlings. For this, it uses two cameras, one at the front and the other at the rear. It is costly because of high-performance computers used during the processing of images. It is capable of navigating stably in muddy ground. It can move at a speed of 20 m/min, operating up to 3 hrs in a single charge.

The weeding robot is equipped with four capacitive touch sensors at the front for detection and an Azimuth sensor at the top towards its rear for measuring the distance covered. The weeding robot uproots the weeds by churning up the soil, thereafter stirring the water to prevent light interception. Absence of photosynthesis kills the weed. Four capacitive touch sensors mounted on the front, right and left detect rice seedlings in muddy and uneven rows, and navigate the robot. Microcomputers control the left and right movement of the wheels, thereby avoiding the seedlings.

Challenges of weeder robots

Owing to current vision systems and algorithms, current weeding robots face numerous challenges in not being able to accurately recognise weeds, navigational complexity, power supply, data management, high cost and maintenance. Not being able to recognise and distinguish between crops and weeds during the early stage of crop establishment leads to the potential of damaging crops. Calibration inaccuracies are another scar in weed management through robots. Soil texture and weed density actively affect weed control efficacy, as herbicide absorption varies with texture.

Failure in intelligent systems to overcome problems posed by changing environmental conditions and production variability due to hostile environmental factors such as dust, extreme temperatures, and humidity. Many efforts have been made to develop intelligent systems to tackle environmental calamities using various detection and avoidance algorithms, but it remains one of the major problems.

Future Prospects

Robotic weed management is a varied, layered approach integrating technological innovations, energy efficiency, and precision engineering. A major development is needed in innovations regarding weed detection algorithms and machine learning tools capable of recognising the difference between weeds and crops under different field and weather conditions. High-resolution camera sensors, coupled with sophisticated multi-layered image processing at all times. Improvements in techniques for herbicide selection and dose calibration. Laser targeting systems can help increase the rate of weed management, particularly for weeds with thick waxy layers. Multiple sensor fusion can be a solution, varying with research innovations in the near future.

Scaling up weeder robots in the marginal farmland of Indian farmers can help optimise energy

ISSN: 3049-2289

consumption. Cost-effective, small, and handy models of weeder robots can facilitate large-scale adoption. The use of solar-powered robots can help achieve the objective. Financial aid and government incentives can be a major driving force for fast, widespread growth. Public-private partnerships can be vital for removing socio-economic constraints along with infrastructural development in rural regions, giving equal and even opportunities for all.

Robotic weed-control machines can help farmers remove weeds more accurately and with less effort than traditional methods, reducing the amount of herbicides needed, which is better for the sustainable environment and saves money. As technology improves, future farming robots will become smarter and more capable of performing more tasks on their own. Overall, these robots will make farming easier, more efficient, and help grow food safely.

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Autonomous LaserWeeder-Carbon Robotics

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Scadoxus multiflorus: An Under-utilized bulbous ornamental with potential for High-Value Floriculture

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Scadoxus multiflorus, commonly known as blood lily or fireball lily, is an ornamental bulbous geophyte belonging to the family Amaryllidaceae and have 2n=16 chromosomes. The species is distinguished by its striking globose inflorescences comprising numerous scarlet flowers, which confer considerable aesthetic and ornamental value. It is naturally distributed across tropical and Southern Africa, extending to the south-western Arabian Peninsula. Despite its distinctive floral architecture and ornamental attributes, S. multiflorus remains comparatively under-utilized relative to commercially established bulbous ornamentals. Recent studies indicates that the species remains under-investigated, particularly with respect to standardized propagation and production technologies. Its distinctive inflorescences offer potential for utilization as a specialty cut flower, premium potted ornamental and landscape plant. Key research priorities include optimization of propagation methods, bulb multiplication, flowering regulation, mineral nutrition, growing substrates and protected cultivation practices. Advanced approaches such as micropropagation and bio-stimulant application may enhance multiplication efficiency, growth, flowering performance and production uniformity. Furthermore, systematic studies on postharvest physiology, vase life, consumer preference and market potential are required to assess its commercial feasibility. Sustainable production, conservation and safe handling should also be integrated into its commercialization, considering the species ethno-botanical and phyto-chemical significance.

Introduction

Scadoxus multiflorus, is a bulbous ornamental species native to a broad region of sub-Saharan Africa, extending from Senegal and Somalia to South Africa. Its natural distribution also includes parts of the Arabian Peninsula, particularly Saudi Arabia, Yemen and Oman, as well as the Seychelles. The species has become naturalized in Mexico and the Chagos Archipelago. It is widely cultivated as an ornamental plant for its conspicuous and brightly coloured flowers and can be grown both in containers and in the ground under suitable climatic conditions. Three recognized subspecies occur within the species, reflecting its geographical and morphological diversity. Common names include blood lily, ball lily, fireball lily, blood flower, Katherine-wheel, oxtongue lily, poison root and powderpuff lily.

Botanical Description

Scadoxus multiflorus subsp. *multiflorus* develops from a rhizomatous bulb, which combines the characteristics of a bulb with the production of rhizomes as modified underground stems. The leaves and inflorescence may emerge simultaneously,

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although foliage development can also occur after flowering. The leaf bases and petioles are closely overlapping, forming a pseudostem or false stem measuring approximately 5-60 cm in length. The inflorescence is borne terminally on a leafless scape measuring about 12-75 cm long, and both the pseudostem and scape may exhibit reddish-brown to dark-violet spotting. The flowers are arranged in a more or less spherical umbel containing approximately 10-200 individual flowers, with each flower borne on a pedicel of about 15-45 mm in length. The tepals, staminal filaments and style are scarlet, gradually fading to pink, while the basal portions of the tepals are fused into a cylindrical tube measuring approximately 4-26 mm long; the free tepals are narrow, spreading and about 12-32 mm long. Following pollination, the fruit develops as a berry measuring approximately 5-10 mm in diameter.

Plate 1. Early developing stage of *Scadoxus multiflorus*

Traditional uses of *Scadoxus multiflorus*

- Plant parts have traditionally been used in parts of Tropical Africa in the preparation of arrow poisons.
- The plant has also been used traditionally in the preparation of fishing poisons.
- Different parts of the plant have been used in indigenous medicinal practices for various purposes.
- Its traditional uses are associated with the presence of biologically active and toxic alkaloidal compounds, highlighting both its ethno-botanical significance and the need for careful handling.

Table 1. Morphological and geographical characteristics of the subspecies of *Scadoxus multiflorus*

Traits	subsp. *multiflorus*	subsp. *katharinae*	subsp. *longitubus*
Flower tube length (mm)	4-15	12-22	15-26
Free segment length (mm)	12-32	18-30	15-28
Free segment width (mm)	0.5-2.5	2.2-4.0	1.4-3.4
Plant height (cm)	55-60cm	Up to 120 cm	Up to 65 cm
Distribution	Tropical and Southern Africa	Eastern Coastal South Africa	Lowland forests of tropical West Africa

Cultivation practices

Scadoxus multiflorus is a chill-sensitive bulbous ornamental and requires temperature management according to its geographical origin. Forms originating from southern Africa should be maintained at a minimum temperature of approximately 5°C, whereas tropical forms require comparatively warmer conditions of around 10°C or above. A porous, well-drained growing medium with a high proportion of organic matter is recommended for successful cultivation. Propagation is primarily carried out through seeds, while pest problems are generally similar to those encountered in other species of the genus Scadoxus.

Plate 2. Peak flowering stage of *Scadoxus multiflorus*

Cultivars and Hybrids

Several artificial hybrids have been developed between *Scadoxus multiflorus* subsp. *katharinae* and *Scadoxus puniceus*. Among them, *Scadoxus* 'König Albert', developed by Johannes Nicolai, flowered for the first time in 1899 and, although rarely cultivated, is reported to multiply rapidly. Another hybrid of the same parentage, *Scadoxus* 'Andromeda', was developed by C. G. van Tubergen around 1904.

The development of these hybrids highlights the potential of interspecific hybridization within the genus *Scadoxus* for producing novel ornamental forms with desirable horticultural characteristics. In addition, *Scadoxus multiflorus* subsp. *katharinae* has received the Royal Horticultural Society's Award of Garden Merit, reflecting its recognized ornamental and horticultural value.

Conclusion

Scadoxus multiflorus is a promising and underutilized bulbous ornamental plant valued for its striking globose inflorescences and unique ornamental appeal. It has considerable potential for use as a specialty cut flower, landscape plant and potted ornamental. However, inadequate production practices, limited propagation methods and lack of standardized cultivation technologies have restricted its commercial exploitation. Therefore, systematic research and development of suitable production technologies are essential for its wider adoption and commercial utilization.

Future scope

Future research should focus on developing rapid and efficient propagation techniques, particularly for large-scale bulb multiplication and uniform planting material production. Further studies on nutrition, flowering regulation and protected cultivation are needed to improve growth, flowering and yield. Research on postharvest handling and storage can help maintain flower quality and extend vase life. Breeding programmes should also be emphasized for developing superior cultivars with desirable flower traits, improved yield and better adaptability, thereby promoting the commercial cultivation and utilization of *Scadoxus multiflorus*.

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El Niño and Indian Agriculture: Precautionary Measures for Climate-Resilient Crop Production

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El Niño events bring erratic and delayed monsoons, prolonged dry spells and rising temperatures, all of which threaten rainfed and irrigated agriculture alike. This article outlines practical, field-tested precautionary measures that farmers can adopt to safeguard crop production during El Niño-affected seasons. Emphasis is placed on soil-moisture conservation through mulching, water-use efficiency through drip and sprinkler irrigation, resilience-building through natural farming practices such as Pre-Monsoon Dry Sowing (PMDS) and millet cultivation, and risk diversification through crop rotation. Together, these low-cost, farmer-friendly interventions can help stabilise yields, protect input investment and strengthen long-term climate resilience at the farm level.

Introduction

El Niño is a climatic phenomenon caused by the periodic warming of sea-surface temperatures in the central and eastern Pacific Ocean. Its occurrence is closely associated with weakened and delayed monsoon activity over India, resulting in below-normal or erratic rainfall, extended dry spells, higher day temperatures and increased evapotranspiration losses. For a country where a large proportion of the cultivated area still depends on the timely arrival and even distribution of the south-west monsoon, an El Niño year translates directly into moisture stress, delayed sowing, poor germination, yield reduction and, in severe cases, complete crop failure.

Farmers cannot control the weather, but the impact of an adverse monsoon can be substantially reduced through timely, well-planned precautionary practices. Moisture conservation, efficient irrigation scheduling, climate-hardy cropping systems and diversification are proven strategies that reduce risk without requiring heavy investment. This article presents a set of such measures suited to small and marginal farm holdings, drawing on mulching, micro-irrigation, natural farming and crop rotation as the four pillars of an El Niño preparedness plan.

1. Mulching

Mulching is one of the simplest and most economical means of conserving soil moisture and moderating soil temperature during periods of deficit and erratic rainfall. A layer of organic or synthetic material spread over the soil surface around the crop reduces evaporation losses, suppresses weed growth, improves soil organic matter (in the case of organic mulch) and protects the root zone from extreme heat.

- **Organic mulch:** Straw, crop residue, dry leaves and farm waste can be used as low-cost organic mulch, and they add humus to the soil as they decompose.
- **Plastic mulch:** Black or silver-black plastic mulch is particularly effective in vegetable, fruit and cash crops, as it conserves moisture, controls weeds and can raise early yields.
- **Timing:** Mulching immediately after sowing or transplanting, while the soil still holds residual moisture, gives the best results.
- **Benefit:** A mulch cover of 5–7 cm (organic) can reduce evaporation losses by 30–50 percent compared with bare soil, a significant saving during a deficit monsoon.

2. Drip and Sprinkler Irrigation

When rainfall is delayed or deficient, every drop of available water must be used with maximum efficiency. Micro-irrigation systems, namely drip and sprinkler irrigation, deliver water directly to the crop root zone or in a fine, uniform spray, cutting down conveyance and evaporation losses that are unavoidable in flood or furrow irrigation.

- **Drip irrigation:** Delivers water and fertigation directly to the root zone, saving 40–60 percent water compared to flood irrigation and improving water-use efficiency in row crops, vegetables, orchards and plantation crops.
- **Sprinkler irrigation:** Well suited to closely-spaced field crops, oilseeds and pulses, ensuring even distribution and helping establish crops during patchy rainfall.
- **Scheduling:** Combining drip with fertigation and scheduling irrigation based on crop growth stage and soil moisture status further conserves water and improves nutrient-use efficiency.
- **Government support:** Subsidy support is available under PMKSY (Per Drop More Crop) for installation of micro-irrigation systems; farmers are encouraged to approach the local KVK or Agriculture Department for guidance.

3. Natural Farming — PMDS and Millet Cultivation

Pre-Monsoon Dry Sowing (PMDS)

Pre-Monsoon Dry Sowing is a natural-farming practice in which seeds of suitable crops are sown dry, ahead of the onset of the monsoon, so that the crop is ready to germinate with the very first effective rainfall. This practice reduces the risk of a sowing-window loss due to a delayed monsoon, ensures better utilisation of early, scattered showers and allows the crop to establish a deeper root system before dry spells set in.

- **Method:** Field bunding and land preparation are completed in advance; seeds are treated with beejamrutham and sown dry in the standing residue or mulch of the previous crop.
- **Suitable crops:** Millets, pulses, oilseeds and certain vegetable crops respond well to PMDS, as their hardy seed coats withstand the pre-sowing dry period.
- **Advantage:** Better plant stand, early crop establishment, reduced dependence on a single sowing window and improved resilience to erratic monsoon onset.

Millet Cultivation

Millets — jowar, bajra, ragi, foxtail millet, little millet and kodo millet — are naturally suited to El Niño-affected, low and erratic rainfall situations. They require significantly less water than paddy or maize, tolerate high temperatures, mature quickly and give a reasonable yield even under moisture stress, making them an ideal climate-resilient alternative during deficit monsoon years.

- **Water and duration:** Millets require 200–400 mm of water against 1,200–1,500 mm for paddy, and complete their life cycle in 70–100 days.
- **Natural farming inputs:** Under natural farming, seed treatment with beejamrutham, soil enrichment with jeevamrutham and ghana jeevamrutham, and mulching together improve germination and moisture retention without dependence on costly external inputs.
- **Policy support:** Additional support is available under the National Millet Mission and the International Year of Millets follow-up programmes for seed, inputs and market linkage.

4. Crop Rotation

Crop rotation — growing different crops in planned sequence on the same field — is a time-tested strategy to spread risk during an uncertain monsoon, improve soil health and break pest and disease cycles. Under El Niño conditions, rotation between a water-demanding crop and a drought-tolerant crop, or between a cereal and a legume, helps stabilise farm income even if one crop in the sequence underperforms.

- **Risk spreading:** Rotate a long-duration, water-intensive crop with a short-duration, drought-tolerant crop (e.g., paddy with pulses/millets) to reduce total-season water demand.
- **Soil health:** Including legumes such as green gram, black gram or groundnut in rotation fixes atmospheric nitrogen, reduces fertiliser cost and improves soil structure.
- **Pest and disease management:** Alternating crop families disrupts the life cycle of pests and pathogens, lowering the need for plant-protection chemicals.
- **Contingency planning:** Where the monsoon is delayed, farmers can substitute a long-duration crop with a short-duration one to fit the reduced growing period, safeguarding the season.

Conclusion

An El Niño year need not translate into a lost agricultural season. With advance planning and the adoption of proven, low-cost practices — moisture conservation through mulching, efficient water use through drip and sprinkler irrigation, resilience through natural farming approaches such as Pre-Monsoon Dry Sowing and millet cultivation, and risk diversification through crop rotation — farmers can significantly reduce the impact of deficit and erratic rainfall on their crops and income. Extension functionaries, Krishi Vigyan Kendras and line departments have a key role to play in disseminating these practices well ahead of the sowing season, so that farming communities are prepared rather than merely reactive when an El Niño event is forecast. Timely awareness, community mobilisation and adoption of climate-resilient technologies remain the surest path to sustainable agriculture under a changing climate.

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Artificial Intelligence (AI) in Agriculture: Revolutionizing the Future of Farming

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Artificial Intelligence (AI) is emerging as a promising technology for addressing the growing challenges of modern agriculture, including increasing food demand, climate variability, water scarcity, declining soil quality and labour shortages. AI enables farmers to use data from crops, soil, weather and digital technologies to make timely and informed decisions throughout the crop production cycle. Its applications include precision farming, crop and soil monitoring, pest and disease detection, weather forecasting, smart irrigation, yield prediction, robotics and farm management. By improving the efficient use of agricultural inputs, reducing crop losses and supporting better decision-making, AI can contribute to higher productivity, profitability and sustainable farming. However, high costs, limited digital infrastructure, lack of technical knowledge, small landholdings and data-related concerns remain important barriers to adoption. With affordable technologies, appropriate training and improved digital connectivity, AI has considerable potential to shape a smarter, more productive and sustainable future for agriculture.

Introduction

The idea of Artificial Intelligence (AI) emerged prominently from the Dartmouth Conference held in 1955, where John McCarthy described the possibility of representing and reproducing human intelligence through machines. (Eli-Chukwu, 2019) Over the years, AI has developed into a broad interdisciplinary field that brings together computer science, mathematics, neuroscience, and engineering. It enables machines to carry out activities commonly associated with human intelligence, including learning, reasoning, perception, and decision-making. (Matyushenko et al., 2020) The rapid advancement of AI in recent years has been supported by increasing computing capabilities, the availability of large volumes of data, cloud-based technologies, and sophisticated computational methods such as machine learning (ML), deep learning (DL), and neural networks (Goodfellow et al., 2016; Russell and Norvig, 2021). As a result, AI is now being increasingly applied in diverse areas such as healthcare, transportation, finance, education, and agriculture.

Modern agriculture is confronted with several serious challenges, including the growing demand for food resulting from population increase, unpredictable climatic conditions, declining soil quality, limited water resources, and shortages of agricultural labour. (Subeesh & Mehta, 2021) In such a situation, conventional farming methods alone may not be adequate to meet these emerging challenges. Artificial Intelligence (AI) offers promising solutions by supporting precision farming, improving the efficient use of agricultural inputs, increasing productivity, and contributing to more sustainable

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and resource-efficient farming practices. (Krastanova et al., 2022)

AI-based agriculture combines digital technologies with biological processes to support better decision-making throughout the crop production cycle, beginning with soil preparation and sowing and continuing through harvesting and post-harvest activities. By providing real-time information on crop conditions and helping farmers anticipate potential risks, AI can facilitate timely preventive measures. This can help minimize crop losses, improve the efficient management of resources, and ultimately enhance farm profitability. (Ma et al., 2022)

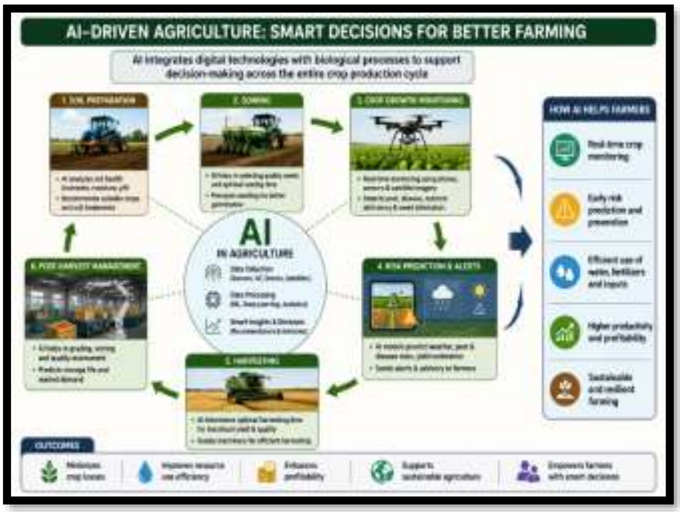

Figure 1. Role of AI in different stages of crop production

❖ Applications of Artificial Intelligence in Agriculture

Artificial Intelligence is gradually becoming an important part of modern farming by helping farmers make faster, more informed and accurate decisions. Its applications cover almost every stage of crop production, from selecting suitable crops and preparing the soil to harvesting and marketing. Some of the major applications of AI in agriculture are discussed below.

1. **Precision Farming:**

AI helps farmers analyse information related to soil, weather, crops and field conditions to determine when and where inputs such as fertilizers, pesticides and water are required. This targeted approach can reduce input wastage, lower production costs and improve overall farm efficiency.

2. **Crop and Soil Monitoring:**

AI-powered systems can use sensors, drones and satellite images to monitor crop growth and soil conditions. Changes in crop health, moisture levels and nutrient status can be identified at an early stage, allowing farmers to take appropriate action before serious damage occurs.

3. **Pest and Disease Detection:**

AI-based image recognition systems can identify symptoms of pests and diseases from photographs of leaves and plants. Early detection enables farmers to take timely control measures, which can reduce crop losses and unnecessary pesticide application.

4. **Weather Forecasting and Risk Prediction:**

AI can analyse weather and historical agricultural data to provide useful predictions related to rainfall, temperature, drought and other weather conditions. Such information can help farmers plan sowing, irrigation, harvesting and other farm activities more effectively.

5. **Smart Irrigation and Water Management:**

AI can help determine the amount and timing of irrigation by considering soil moisture, weather conditions and crop requirements. This supports efficient use of water and can be particularly valuable in areas facing water scarcity.

6. **Yield Prediction:**

By analysing factors such as weather, soil characteristics, crop growth and previous production records, AI can assist in estimating crop yields. Such predictions can help farmers plan harvesting, storage and marketing activities in advance.

7. **Intelligent Farm Machinery and Robotics:**

AI is also being integrated into tractors, drones, robots and other agricultural machinery. These technologies can assist in activities such as seeding, weed detection, spraying, harvesting and crop monitoring, thereby reducing dependence on manual labour and improving operational efficiency.

8. **Market and Decision Support:**

AI-based platforms can analyse market trends, prices and other relevant information to support farmers in making better decisions regarding crop selection, timing of sale and marketing strategies. This can improve access to information and potentially strengthen farm profitability.

(Matyushenko et al., 2020; Gryshova et al., 2019 & Nassivera et al., 2017)

Figure 2. Applications of Artificial Intelligence in modern agriculture

Benefits of Artificial Intelligence in Agriculture

The use of Artificial Intelligence in agriculture can bring several benefits to farmers and the wider agricultural sector. By combining farm data with intelligent analysis, AI can support better decisions, improve the use of resources and make farming more responsive to changing conditions.

1. Improved Productivity:

AI can help farmers identify the right time and method for carrying out different farming operations. Better monitoring and timely decisions can contribute to healthier crops, improved yields and more efficient production.

2. Efficient Use of Agricultural Inputs:

AI-based systems can help determine the appropriate quantity and timing of water, fertilizers and plant protection measures. This can reduce unnecessary input use, lower production expenses and improve resource-use efficiency.

3. Early Identification of Risks:

AI can detect early signs of pest attacks, diseases, nutrient deficiencies and unfavourable weather conditions. Early warnings allow farmers to respond before problems become severe, thereby reducing the possibility of major crop losses.

4. Reduction in Production Costs:

Automation and data-based decision-making can reduce unnecessary labour, input use and repeated field operations. Over time, this can help farmers manage their production costs more effectively.

5. Better Resource Management:

AI supports the efficient management of important resources such as soil, water, fertilizers and energy. This is particularly important in regions where agricultural resources are limited or under increasing pressure.

6. Support for Climate-Resilient Farming:

Changing weather patterns create uncertainty for farmers. AI can assist in analysing weather information and identifying potential risks, helping farmers plan agricultural activities and adopt suitable measures to cope with climatic variability.

7. Enhanced Farm Profitability:

Better production decisions, reduced input wastage, lower losses and improved access to market information can contribute to higher economic returns. AI can therefore support farmers in making farming more productive and financially sustainable.

8. Promotion of Sustainable Agriculture:

By encouraging precise application of inputs and better use of natural resources, AI can help reduce the environmental impact of farming. Its integration with sustainable agricultural practices can contribute to long-term productivity while conserving soil, water and other resources.

(Bao & Xie, 2022; Kurgat et al., 2020; Ma et al., 2022; Delcheva, Nencheva &Penev, 2021)

Challenges in Adopting Artificial Intelligence in Agriculture

1. **High Cost:** AI tools and smart farming equipment can be expensive for small and marginal farmers.
2. **Lack of Technical Knowledge:** Many farmers need training to understand and use AI-based technologies effectively.
3. **Poor Digital Infrastructure:** Limited internet connectivity, electricity and access to digital devices can restrict AI adoption.
4. **Limited Awareness:** Lack of information about AI applications may make farmers hesitant to adopt new technologies.
5. **Small Landholdings:** The cost of advanced AI technologies may not be economically suitable for farmers with small or fragmented farms.
6. **Data and Privacy Issues:** Reliable agricultural data and proper protection of farmers' digital information are important concerns.
7. **Language Barriers:** Complex technical information may be difficult to understand without simple, local-language support.
8. **Lack of Technical Support:** Regular maintenance, updates and expert assistance are needed for the effective use of AI systems.

(Ganeshkumar et al., 2023 & Javaid et al., 2023)

Future Prospects of Artificial Intelligence in Agriculture

The future of AI in agriculture appears promising, with continued advancements expected to make farming more intelligent, precise and sustainable. Some important areas of future development include:

1. **Autonomous Farming:** AI-powered tractors, robots and machinery may perform several farm operations with minimal human intervention.
2. **Smart Farmer Advisory:** AI can provide farmers with personalized recommendations based on their crops, soil, weather and local conditions.
3. **Advanced Crop Monitoring:** Drones, satellites and AI can work together to detect crop stress, pests and diseases at an early stage.
4. **Improved Weather and Yield Prediction:** More advanced AI models can provide accurate forecasts to support better farm planning.
5. **Efficient Resource Management:** AI can help farmers use water, fertilizers, energy and other inputs more precisely.
6. **Integration with IoT:** Combining AI with sensors and Internet of Things (IoT) technologies can enable real-time monitoring and automated farm management.
7. **Climate-Smart Agriculture:** AI can support farming practices that are better adapted to changing climatic conditions while reducing environmental impacts.
8. **Greater Accessibility:** The development of affordable and easy-to-use AI solutions can make smart farming technologies more accessible to small and marginal farmers.

(Sharma et al., 2020; Talaviya et al., 2020 & Singh et al., 2021)

Conclusion

Artificial Intelligence is opening a new chapter in modern agriculture by making farming more data-driven, precise and efficient. From crop monitoring and disease detection to smart irrigation, weather forecasting and yield prediction, AI can help farmers make better decisions and use limited resources more effectively. Although challenges such as high costs, limited digital infrastructure and lack of technical knowledge remain, these barriers can be addressed through affordable technologies, farmer training and improved rural connectivity. With continued innovation and wider accessibility, AI has the potential to make agriculture more productive, sustainable, climate-resilient and profitable, ultimately paving the way for a smarter future of farming.

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Lingonberries

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Lingonberries, scientifically *Vaccinium vitis-idaea* L, commonly referred to as partridgeberry, or cowberry, are a dwarf perennial and evergreen shrub belonging to the Ericaceae family. Lingonberry is a short, mat-forming, evergreen shrub and a very hardy plant, resilient to acidic soil conditions and sub-zero temperatures (Sharifi *et al*, 2024). It shares its taxonomy with the blueberry (V. myrtillus) and the cranberry (V. macrocarpon), both belonging to the same genus, *Vaccinium.* They are Native to Northern Europe, Russia, Canada, and Alaska. Historically, they have been utilized as a staple dietary resource by Scandinavian people and other indigenous peoples of North America (Hjalmarsson and Ortiz, 2001). Its fruit is four-celled, globular, and bright to dark red in colour (Tirmenstein, 1991). Lingonberries have been identified as a functional food with a high amount of bioactive compounds like anthocyanins (predominantly cyanidin-3-galactoside), flavonols, and proanthocyanidins with various health-promoting properties.(Kowalska, 2021).

Botanical description

Lingonberries are genetically heterozygous dicot angiosperms (Debnath, 2006). They are small evergreen dwarf shrubby plants that propagate through subterranean rhizomes, thereby forming dense colonies (Raudone & Vilkickyte, 2021). The plant reaches a height of 10-30 cm. The cross-section of stem stem shows anatomically triangular pith, which differentiates it from other species of the Vaccinium genus (Schweingruber & Steiner, 2003). The fruit is bright to dark red in colour, with a strong acidic flavour, and weighs between 0.17 and 0.45 grams. (Tirmenstein, 1991).

Loingonberries are classified into two main types of subspecies by Hulten (1949):

Wild type / North American type (V. vitis-idaea Ssp. Minus): This subspecies is mainly distributed through Iceland, Greenland, North America, Northern Asia, and Scandinavia. It is considered a wild species and is not encouraged in commercial cultivation. It is a small arctic race that generally grows up to 20 cm tall. It has small leaves yielding only one crop per year. (Debnath & Arigundam, 2020). The leaves are leathery, oval, and alternate, with the upper surface dark green and the bottom side light green. (Penhallegon, 2006)

European type (V. vitis-idaea Ssp. vitis-idaea): This subspecies is distributed throughout Europe and Asia. This type is suitable for commercial cultivation with active breeding programmes. It is a large lowland race that generally grows taller than the wild type. It grows up to 30 cm tall with leaves larger than wildtype. It yields two crops per year. (Debnath & Arigundam, 2020). The branches bear five to nine glossy evergreen leaves in bright or dark green colour. (Penhallegon, 2006).

Common uses

Lingonberries can be eaten fresh or prepared into jams, juices, or syrups. The high concentration of benzoic acid in lingonberries acts as a natural antimicrobial agent, thereby improving the shelf life of the berries and making them a potential bioactive dietary resource. (Dro´zd et al, 2017). But due to the high concentration of phenolics, the prepared products may have a little bit of astringency or bitterness, or sourness, which limits their use in the food and beverage industry (Laaksonen *et al* 2016). However, some alcoholic beverages have been prepared from lingonberries via benzoic acid decrement through baker's yeast incubation of juice and through the use of saccharomyces and non-saccharomyces yeasts (Saini et al 2024).

Lingonberries not only possess organoleptic qualities, but they are also a food of medicinal importance due to the presence of antimicrobial and antioxidant chemicals in the fruit. Historically, they have been used in the treatment of fever, diarrhea, and rheumatism (Hjalmarsson & Ortiz, 2001). They are known as superfruits due to the presence of high concentrations of vitamins C, A, and E and polyphenols (Kowalska, 2021). Due to their high concentration of antioxidants, they can have an important role in protecting cells from oxidative damage, which can lead to cancer, cardiovascular and degenerative diseases, and chronic inflammation (Dinstel et al, 2013).

Today, berry picking from lingonberries has become a recreational activity, and now the lingonberry plants have found their new utilization as ornamental plants. Therefore, lingonberry plantations can benefit the human race in multiple dimensions: food, beverages, medicines, and recreational activities.

Climate and soil

Lingonberry is quite hardy and can grow in a wide range of places, from dry, exposed slopes and peat soils to ombrotrophic bogs (Raudone & Vilkickyte, 2021). Dormant plants can tolerate temperatures around -40°C (Holloway, 1984); however, this hardiness comes when there is enough snow cover to insulate underground rhizomes and green foliage. In the absence of snow cover, the green leaves are susceptible to photooxidative stresses and desiccation; therefore, the plants should be protected with straw mulch, overhead irrigation, or floating row covers. (Penhallegon, 2006). Photoperiod length is an important criterion in flower initiation. The plant usually requires a day length of 8 to 12 hours for flower initiation (Stang et al., 1993).

Lingonberries are often regarded as low-maintenance plants suited to acidic and nutrient-deficient soils, with lower nutritional demands than many other fruit-bearing plants. However, to explore the full potential of the crop and grow it commercially, they need precise care and management practices (Karlsons et al, 2021). Lingonberries need soils with good drainage and a sufficient amount of organic matter. As indicated by Penhallegon (2006), an organic matter level of 2%–6% in the top 3–6 inches and with a soil pH of 4.3–5.5 is needed for excellent production of berries. The European blueberry and Cranberry require similar soil conditions. Lingonberries prefer nitrogen in ammonium (NH_4^+) form rather than nitrate (NO_3^-) form because the ammonium uptake is much more rapid than nitrate uptake (Ingestad, 1973). Lingonberries are sensitive to high concentrations of salts, particularly sodium and chlorine, and excess calcium levels are also harmful to the plants (Penhallegon, 2006).

Flowering and pollination

Lingonberries flower in clusters of 4 to 6 on drooping racemes on one-year-old growth. Flowers are white in colour with a slight red tinge. Each flower has 4 to 5 petals and 8 to 10 stamens (Aparaschive et al., 2024). The flowers grow epigynous and hermaphrodite, with 15–20 ovules per carpel and 4–5 locules per ovary (Hjalmarsson,1997). Flowering time varies from place to place depending on climatic conditions; for example, in southern Scandinavia, flowering occurs from May to June (Hulten 1971), in Alaska, flowering starts from June (Holloway 1984). The fruit takes 78-84 full days for proper ripening (Holloway, 1982). In some cultivars, repeat flowering can also be observed from mid-July (Gustavsson, 2001). The fruit becomes ripe from mid-August to mid-October, depending on the time of flowering and climatic conditions.

For good fruit production, lingonberries need pollination from pollinizers. For optimal pollination and the highest output, it is recommended to plant 10% pollinizer cultivars. Red Pearl and Sussi are two well-known pollinizer cultivars (Penhallegon, 2006). The flowers are self-compatible but show inbreeding depression on self-pollination (Eriksson, 1989). Honey bees and bumblebees are the main agents of entomophilous cross-pollination in lingonberries

(Jacquemart, 1993). During the blooming period, low temperatures such as minus 2°C can damage flowers, disrupt pollination, and negatively impact fruit development (Penhallegon, 2006).

Propagation

Lingonberries can be propagated with the help of seed, stem cuttings, or rhizome cuttings (Tirmenstein, 1991). Seeds are extracted from fully ripened berries by maceration. For germination seeds require stratification for 30 days at 4°C before sowing. Pure acid-milled peat is considered the best medium for germination of seeds (Paal, 2006). Propagation through stem cuttings fails to produce rhizomes, while propagation via rhizome cuttings has no such disadvantage (Holloway,1984). Propagation material, such as shoot cuttings, should be collected early in spring, before bud break, or late in summer, for better rooting (Paal. 2006).

Micropopagation is a more suitable and efficient method of propagation for lingonberries. Tissue-cultured plants were found to be superior in terms of fruit set, plant growth, and rhizome production than stem propagated plants (Paal. 2006).

Planting

Lingonberries can be planted in the spring or autumn. Preferably, new plants are planted in the middle of raised rows. Recommended spacing of plants is 20-46 cm from plant to plant and 61 to 91 cm from row to row. After four years of planting whole bed will be covered with new plants automatically propagated through rhizomes. Care should be taken while planting to hide all the roots under the soil. The roots are usually only 5-7 cm deep. The recommended planting density averages around 8700 plants per acre. The average suggested planting density is 8,700 plants per acre, (Penhallegon, 2006).

Mulching

Weed control is one of the main problems in lingonberries since their growth is seriously affected by weeds (Gustavsson, 1993). Mechanical weed control is avoided due to shallow roots, and some chemical weedicides have also been found to have a detrimental effect on the lingonberry plants (Gustavsson, 1999). So mulching offers an effective way to control weeds. It also offers maintenance of proper soil moisture. Researchers have experimented with various kinds of mulches like seed straw, leaf or bark mulch, wood chips, Sphagnum peat, manure, mint compost, and pine forest duff, but for commercial purposes, after planting, cover the base of the plants with 4–6 inches of organic material. For rhizome-forming cultivars like "Sussi," Plastic foil mulches should be avoided (Saario & Voipio, 1997). However, plastic mulching can be found advantageous in reducing frost injuries (Gustavsson, 1999).

Nutrient management

As already discussed, lingonberries can grow on poor soils as well; they don't require intensive nutrient management practices. In fact, excess use of fertilisers can cause dieback. With leaves turning brown or black (Penhallegon, 2006). Lingonberries show pronounced sensitivity to high concentrations of salts (Ingestad, 1973). However, 10–20 kilograms of nitrogen can be applied per acre annually (Penhallegon, 2006). Some studies have shown that Plants cultivated in peat displayed the maximum vegetative development based on the number of new shoots, shoot length, and dry weight per plant after three growing seasons, demonstrating that peat is the best growing medium (Holloway et al, 1982). Keep in note that fertilizer response can vary in different varieties.

Irrigation

Experiments have shown that lingonberries show the property of embolism, which is ability to recover from drought when sufficient water supply is restored (Ganthaler & Mayr, 2015). As lingonberries are highly sensitive to salt concentrations, this underscores the need of small frequent irrigations and avoidance of drought conditions (Hjalmarsson &

Ortiz, 2001). While as prolonged melt water flooding have shown to cause death of dwarf shrubs. (Zubkova et al, 2022). These points shows the need of well established irrigation management system in lingonberry plantations, which can be done with the help of drip or trickle irrigation. For better plant establishment and less sunburn, use irrigation should be used all throughout the first summer (Penhallegon, 2006).

Pruning

During the first few years of planting, no pruning is advised. After the fourth year of plantation, plants should be clipped to a height of five centimeters to encourage more shoot formation for the production of more bearing branches. Saario (2005) showed that pruning up to 5cm length encouraged a greater number of new shoots.

Cultivars. (Vilkickyte et al 2022**)** (Finn & Mackey 2006). (Paal 2006) (Gustavsson 1993)

1. Kostromička': this cultivar originates from Russia. It has very high phenolic content in leaves (81–82 mg/g DW). It is considered one of the superior cultivars with high terpenoids (both acids and neutral). It is a medium-sized variety with good yield performance and extreme cold tolerance.
2. Kostromskaja rozovaja: this cultivar is also from Russia, similar to kostromicka, with the highest anthocyanin content and high arbutin in leaves. It is a 15-18 cm tall cultivar, but produces large berries.
3. Rubin: It is one of the genetically rich cultivars originating from Russia with the highest phenolic (20.4 mg/g) and terpenoid content in fruits (10.3 mg/g). it is also a medium-sized plant with an approximate berry weight of 2.2 grams. It was released in the 1990s in Russia.
4. Erntedank: It is a German-originated cultivar with one of the lowest levels of neutral triterpenoids, but it contains the highest amount of resveratrol. It is a vigorous, upright to semi-upright plant. It yields medium to large fruits with firm red berries.
5. Erntekrone: It is also a German-originated cultivar with high benzoic acid and low arbutin content.it is a high-yielding, vigorous upright plant, reaching up to 30cm in height. It blooms twice a year and produces bright red berries; its foliage is somewhat rounded with dark green in colour.
6. Erntesegen: it is a German-originated cultivar with high amounts of Benzoic acid (3.01 mg/g), trans-cinnamic acid, and moderate in phenolic content. It is a low to medium-sized plant but spreads readily through underground rhizomes. It produces relatively wide berries with deep red colour. It is described as one of the highest yielding European cultivars.
7. Koralle: It is a Dutch-originated cultivar with a unique property among other cultivars of having a high number of free amino acids, but low triterpenoid acids. It is a highly vigorous cultivar that blooms twice a year, first in April, then in July. It yields berries of intermediate weight and low in acidity.
8. Masovia: it is a cultivar from Polish origin low in flavonoids but high in proanthocyanins. It is known for vigorous growth habit and extensive rhizome production.
9. Sanna and Sussi: These are two similar cultivars from Swedish origin. Both cultivars are low in A-type proanthocyanidins. These are low in vigour with poor adaptation, twig dieback is commonly observed in these cultivars. It blooms only once in the year and berries weigh around 0.28 and 0.20 grams, respectively. They contrast in their growth habit where Sussi is spreading (10 – 20 cm height) while Sanna is erect in growth habit (15 – 30 cm height)

Yield

Lingonberry yield varies with respect to climatic conditions, geographical location and varieties. They are harvested with a hand rake also uded to harvest lowbush blueberries A lingonberry plantation can be expected to remain productive for over 20 years (Penhallegon, 2006). The highest yields in Swedish forests and bogs were 13.8 and 17.3 kg per hectare (Hjalmarsson & Ortiz, 2001). While Kardell (1979) reported yield per hectare for lingonberries is between 6.1 and 7.1 kg fresh weight. But modern commercial plantations' yields are comparable to the yield of blueberries and lingon berries, for example, in the U.S, yields range from 2–15 tons per acre, Germany (0.5–6 tons per acre), Sweden (1–3.6 tons per acre (Penhallegon, 2006).

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Biofortification is the future of nutritional security

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During the COVID-19 pandemic, micronutrient supplementation has achieved immense importance and has become a topic of interest because of its potential in supporting immunity and overall health benefits. Iron, zinc, iodine, and selenium deficiency in human diets are significant food-related issues worldwide. Hidden Hunger, a micronutrient deficiency condition where the body lacks essential vitamins and minerals that are required for human growth and development. Micronutrient deficiencies affect approximately 3 billion people worldwide, thereby hindering the development of of socio and economic development of human potential in developing countries. United Nations second Sustainable Development Goal was to eradicate malnutrition and hidden hunger. Traditional agricultural approaches can marginally enhance the nutritional value of some food supplements; biofortification is a process of increasing essential vitamins and minerals in edible portions of crop plants through agronomic intervention and genetic selection, which is a sustainable as well as long-term strategy for addressing micronutrient deficiencies in rural populations in developing countries.

Introduction

Over 2 million individuals, or one in three people, are affected by micronutrient deficiency globally (FAO *et al,* 2015). An estimated 4 billion and 2.7 billion people have iron and zinc deficiency, respectively. Hundreds of millions lack one or more essential vitamins, which has a negative impact on health and socio-economic conditions (WHO, 2002; Hotz and brown,2004: UN-SCN, 2004). Malnutrition worldwide, mostly in developing countries, is likely to increase to 8 billion by 2030. Micronutrient deficiency is one of the major factors for increased mortality and morbidity. An estimated 1.1 million out of 3.1 million infant deaths occur due to micronutrient deficiencies yearly.

What causes malnutrition? Disbalance in food systems that could not provide nutrients in a proper and balanced manner required for promoting healthy factors required for health life in a sustainable manner. It's even more related to the agricultural system because the majority of the food system is dependent on agricultural products for their source of nutrients. Unfortunately, the agricultural system is explicitly designed to promote profitability for farmers and agricultural industries.

Agriculture system during the mid- 20th century onwards successfully addressed the challenge of feeding the poor during "Green Revolution" by concentrating mainly on three staple crops-rice, wheat, and maize. These crops helped in mitigating the effects of widespread famines in many developing countries. However, current statistics of nutritional deficiencies mark the fact that "Green Revolution" was a short-term answer to the problem of hunger. No doubt it increased production, but the nutritional factor was lacking. Major dependence on calorie-rich foods and lesser attention to the production of non-staple foods like fruits, vegetables, and lentils led to scarcity, created a vacuum for less production and more demand, ultimately leading to a rise in price that ultimately created a problem called hidden hunger. Population growth, along with climate change due to faulty and negligent practices, has also led to extreme hunger in some parts of the world where there was no nutritional or food security.

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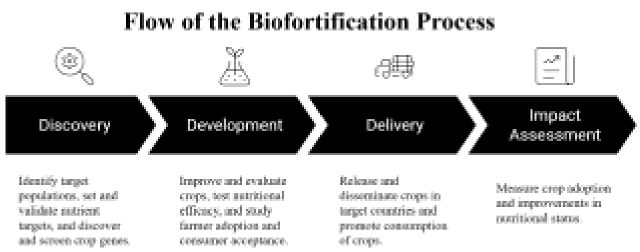
In India, over 21.9% of the population is under extreme poverty with limited access to resources.

Dietary diversification, pharmaceutical supplementation, industrial fortification, and food supplementation are key intervention strategies. However, such interventions have selective success mostly due to socio-economic constraints. Diversity in diet is by far the most desirable and sustainable solution, but only a few can enjoy it because of financial constraints. A novel concept brought into light at present is "biofortification", where nutrients are added into regular habitual diets to improve the nutritional quality of food. "Biofortification" is precisely described as *"fortification in the field rather than in the factory"*.



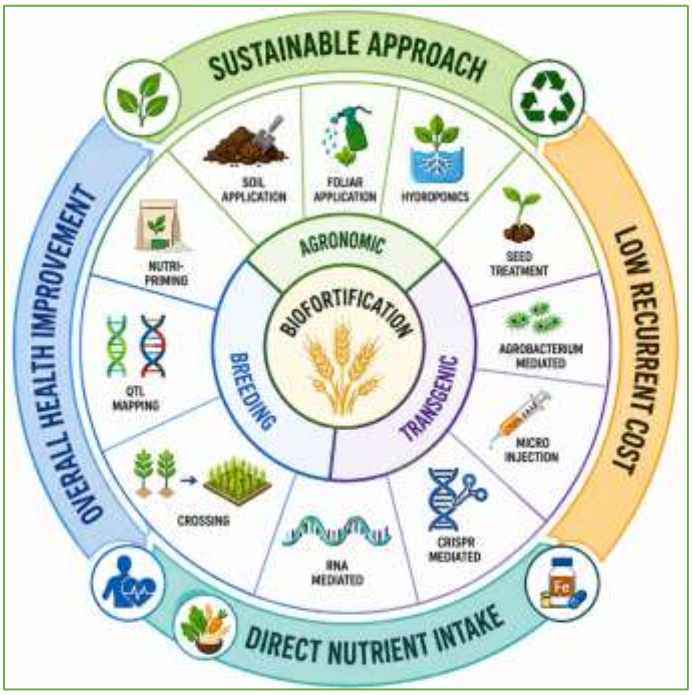
Biofortification

Biofortification is the process of increasing the density of vitamins and minerals in micronutrient-rich staple crops using the best traditional breeding practices and modern biotechnology i.e., plant breeding, transgenic techniques, or agronomic practices, with the objective of providing long-term, cost-effective, sustainable staple crops such as wheat, rice, maize, and millets with more micronutrients. Biofortification aims to enhance the concentration and bioavailability of essential nutrients in food crops during their growth and development. This approach provides a cost-effective and sustainable long-term solution to improving nutritional health. Biofortification mainly focuses on integrating desirable nutritional traits in preferred agronomic and consumption traits, such as high-yielding varieties of crops. In this way, it creates a healthy market for farmers as well as for consumers who are unwilling to pay a premium price.

The following considerations are important for the successful development and implementation of biofortified crops:

1. Biofortified crops should be high-yielding and profitable from the farmers' point of view.
2. In the targeted regions where there is malnutrition, biofortified crops should be accepted by both farmers and consumers.
3. An adequate amount of staple foods must be regularly consumed by the people of different groups and sexes.
4. Post-harvest nutrient degradation loss should not occur during storage, processing or cooking.
5. Bioavailability of nutrients must be present, allowing them to be effectively absorbed and utilised by the body.

The impact pathway is demonstrated below, consisting of Discovery, Development, Delivery and Impact Assessment.



Forms of Biofortification

The biofortification techniques,

1. Agronomic biofortification

2. Improvement of plant varieties through
    - Conventional breeding
    - Transgenic/Genetic engineering

Agronomic biofortification

Agronomic biofortification involves the enrichment of the nutritional value of crops through fertilization and soil management. . Agronomic biofortification focuses on improving solubilization and mobilization of minerals. The effectiveness depends upon the soil composition, the solubility and mobility of minerals, the ability to absorb minerals, and the accumulation of bioavailable minerals in non-toxic levels in the edible parts of the crops. Agronomic biofortification primarily focuses on increasing the mineral content of crops.

To increase the concentration of micronutrients in the edible portions of crops, organic or inorganic micronutrient fertilizers, as well as biofertilizers, are applied through soil or foliar application. Soil application is more common when nutrients are required in large amounts. Foliar application is more economical and applicable when nutrient deficiency symptoms are evident in crops. Foliar nutrient application is considered superior to soil application for agronomic biofortification, as it enhances the concentration of micronutrients in crop tissues rather than simply contributing to higher yields. However, it is costly and could easily be rinsed off by rainwater. Foliar application is generally more effective when applied during the flowering and early milk stages of crop development, as it's the phases where absorption of nutrients for fruit formation begins. The efficiency of foliar nutrient application is enhanced under warm and humid conditions during the early morning and late evening.

The concentration of micronutrients in crops is influenced by the type of fertilizer, its application method and rate, the timing of application, and the movement of nutrients within the plant. Advances in specialized fertilizer formulations, including water-soluble, chelated, and nano fertilizers, have significantly enhanced the effectiveness of agronomic biofortification by improving nutrient absorption and transport to the edible portions of crop plants. Nanoparticles, owing to their extremely small size and distinctive physicochemical properties, have emerged as promising tools for crop biofortification.

Conventional breeding

Biofortification through conventional breeding aims at improving the concentration and bioaccessibility of minerals in crops by utilizing the genetic differences between crops of similar species. It focuses on techniques of introducing genotypes that will enhance the uptake, transport and redistribution of minerals to improve the efficiency of biofortification. Plant breeding-based biofortification focuses on developing staple food crops with enhanced micronutrient concentrations, thereby contributing to improved nutritional security, particularly among low-income households. It is highly sustainable because nutritionally enhanced crop varieties can be cultivated and consumed continuously, even if government support and international funding for micronutrient programs decline.

Currently, about 299 varieties of biofortified cops have been released in over 30 countries via conventional breeding. Conventional plant breeding-based biofortification is widely regarded as a safe approach and is generally accepted because it does not raise the biosafety and public concerns often associated with genetic engineering.

Transgenic/genetic engineering

Biofortification has adopted a two-tiered strategy in which conventional breeding is the preferred method for enhancing crop nutritional quality, while genetic modification is employed only when the desired traits cannot be achieved through breeding alone. Genetic engineering transfers only selected genes rather than large segments of genetic material, thereby reducing the possibility of unwanted traits being inherited alongside the desired trait. Another aspect of nutritional genetic modification is the reduction of antinutritional compounds, such as allergens, glycosides, and phytates, to improve nutrient absorption.

Two key factors should be considered in genetic modification. First, the acceptance of biofortified crops by farmers and the effectiveness of the associated seed distribution systems must be evaluated. Second, comprehensive assessments of their nutritional, social, and economic impacts are essential.

Genome editing, also referred to as gene editing, enables the precise insertion, deletion, or modification of DNA sequences in a wide range of cells and organisms. It also offers the potential to develop genetically modified crops without introducing foreign genes, thereby addressing many of the regulatory concerns associated with transgenic crops. To enhance the effectiveness of transgenic biofortification, omics technologies have been incorporated to improve the identification and manipulation of genes associated with nutritional traits. It provides an integrated understanding of the relationships among genes, transcripts, proteins, metabolites, and nutrients, thereby enabling comprehensive analysis of the molecular networks involved in nutrient biosynthesis, transport, and accumulation. Transcriptomics, Proteomics, Metabolomics, and ionomics technologies of omics have been used in studies involving biofortification of lysine, Ca, Zn, Fe, and vitamin C in PBFs.

Justification for biofortification Advantages

1. ***Comparative advantages of biofortification***

Micronutrient deficiencies cannot be addressed through a single intervention; therefore, biofortification serves as a complementary strategy. Biofortification, however, has two key comparative advantages:

- Long-term cost-effectiveness
- Ability to reach underserved, rural populations.

Biofortification puts a solution in the hands of farmers, combining the micronutrient trait with other agronomic and consumption traits that farmers prefer.

2. ***Cost-effectiveness***

Ex-ante evaluations have shown that biofortification is a cost-effective nutritional intervention. Each dollar invested in biofortification can produce economic benefits of up to US$17.

3. ***Nutritional bioavailability and efficacy***

Iron crops: Biofortified iron-rich beans and pearl millet improve iron status and nutritional health.

Vitamin A crops: Provitamin A in biofortified crops is efficiently converted into retinol in the human body.

Zinc crops: Zinc in biofortified wheat is highly bioavailable and improves dietary zinc intake.

Global Hunger Index

The Global Hunger Index (GHI) is a tool for comprehensively measuring and tracking hunger at global, regional, and national levels.

GHI scores are based on the values of four component indicators:

The global hunger situation has shown little improvement, with the Global Hunger Index (GHI) score changing only from 19.0 in 2016 to 18.3 in 2025, leaving hunger classified as a moderate concern. Countries such as Angola, Bangladesh, Ethiopia, India, Nepal, and Sierra Leone demonstrate that targeted policies and sustained investments can reduce hunger, although continued support and resilient food systems are essential to maintain these gains. GLOBAL HUNGER INDEX 2025 score for South Asia is 24.9. The score indicates that hunger in the region remains serious.

India reflects this broader trend of uneven progress. 2025 GHI for India is serious but continues a gradual improvement. Undernourishment has declined slightly since 2021 but continues to affect 172 million

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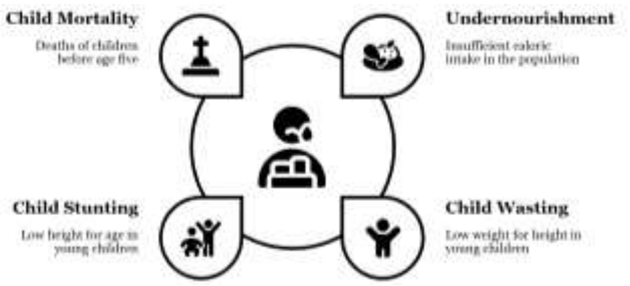
people, i.e. 13.5 million people more than in 2016. Child stunting has declined yet remains extremely alarming at about one in three children. Child wasting shows slight improvement, keeping India in the extremely alarming category.



In 2025, GHI ranked India at 102 with a GHI score of 25.8 under the serious category, with a 13.6% change since 2016.

Future prospects

Although biofortified crops are recognized for improving micronutrient status, further research using sensitive biochemical and functional indicators is needed to fully evaluate their health benefits. It is becoming an increasingly important area of study as the global population continues to increase and the demand for nutrient-rich food is growing. The future prospects for biofortification are :

- Expanding the range of biofortified crops
- Improving the efficiency of biofortification
- Improving the distribution and access to biofortified crops
- Promoting awareness and understanding of biofortification:
- Reducing malnutrition and improving public health
- Supporting sustainable development
- Improving gender equity

Conclusion

Biofortification has been projected to be the most sustainable solution to malnutrition and hidden hunger. Biofortification is principally aimed at improving nutritional security in developing countries and rural communities; however, its applications and benefits also extend to populations in the developed world. It is the most sustainable method among other interventions. Despite its potential, the successful implementation of biofortification programs is constrained by challenges such as the limited availability of biofortified crop varieties, high production costs, inadequate awareness, restricted distribution and access, and political and regulatory barriers.

One of the biggest challenges of biofortification is public acceptance. The widespread acceptance of biofortified crops requires enhanced public education and awareness, despite the established scientific consensus regarding the safety of genetically engineered crops. Moreover, the integration of conventional breeding, marker-assisted selection, and genetic engineering provides a promising strategy for developing high-yielding cultivars with enhanced micronutrient concentrations and improved nutrient bioavailability. Biofortified crops can greatly enhance the health and well-being of millions of underprivileged people in India through effective implementation and relatively low research investment.

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Beyond Yield: What makes a mushroom farm sustainable?

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Mushroom cultivation has a unique place in agriculture. Many cultivated mushrooms can utilize lignocellulosic materials such as straw, sawdust and wood-based residues as substrates, converting relatively low-value biomass into a valuable food product (Grimm and Wösten, 2018). But does this mean that every mushroom farm is sustainable? Not necessarily. A farm may achieve high production but consume considerable energy. Another may utilize agricultural residues efficiently but struggle to remain profitable. A third may generate large quantities of spent mushroom substrate without finding a productive use for it. Sustainability therefore needs to be viewed beyond yield alone. Studies assessing mushroom production systems have similarly highlighted the importance of resource use, energy, substrate management and production efficiency in determining environmental performance (Robinson et al., 2019; Jasińska, 2023).

A sustainable mushroom enterprise therefore needs to balance economic viability, environmental responsibility and social well-being.

1. Economic Sustainability: Can the farm remain viable?

For growers, sustainability begins with economics. An enterprise that cannot generate adequate returns over time cannot remain viable, irrespective of how efficiently some of its resources are being used. Yield and biological efficiency are important, but they tell only part of the story. Growers must also consider the costs of substrate or compost, spawn, labour, electricity, packaging, transportation and other inputs. Improving productivity from the resources already being used is therefore an important route towards sustainability. Better crop management, reduced contamination and production losses, efficient utilization of growing-room capacity and improved market linkages can help growers obtain greater value from their investment.

Diversification may also help reduce business risk. Depending upon local conditions, growers can explore different mushroom species, products and marketing channels rather than depending entirely upon a single product or market.

2. Environmental Sustainability: How efficiently are resources being used?

One of the environmental strengths of mushroom cultivation is its ability to utilize lignocellulosic materials and agricultural by-products as growing substrates (Grimm and Wösten, 2018). However, mushroom production itself requires resources. In climate-controlled farms, electricity and fuels may be required for cooling, heating, ventilation, humidification and other operations. A life-cycle assessment of button mushroom production in the United States identified electricity and fuel use, along with compost-related processes, among the important contributors to environmental impacts (Robinson et al., 2019). More recent European research has also demonstrated considerable variation among production systems in energy use, substrate use and yield (Goglio et al., 2024).

For growers, improving resource efficiency can begin with relatively straightforward measures:

- proper maintenance of insulation and climate-control equipment;
- avoiding unnecessary energy consumption;

- efficient use of water;
- reducing avoidable plastic use;
- minimizing production losses; and
- considering renewable-energy options where technically and economically feasible.

Recent research on low-carbon mushroom production also identifies energy management, waste utilization and improved production technologies as important areas for enhancing sustainability (Patel et al., 2025).

Spent Mushroom Substrate: Waste or Resource?

An important by-product of mushroom cultivation is spent mushroom substrate (SMS); the material remaining after completion of mushroom production.

Rather than considering SMS only as waste, research has examined its potential use in compost and soil improvement, subsequent mushroom cultivation, animal-related applications, energy production and other value-added uses (Grimm and Wösten, 2018; Leong et al., 2022).

This creates a simple but important question for every mushroom grower:

What happens to the substrate after the crop is over?

Unmanaged accumulation creates a disposal problem, whereas finding an appropriate local use can potentially turn the residual substrate into a useful resource. The best option, however, will depend upon mushroom species, substrate composition, location and the availability of nearby users or markets.

3. Social Sustainability: What about the people behind production?

Sustainability also has a human dimension. Mushroom enterprises involve labour in substrate preparation, spawning, crop management, harvesting, grading, packaging and marketing. Fair wages, safe working conditions, appropriate protective measures and opportunities for skill development can contribute to a stronger and more sustainable enterprise. Training and institutional linkages can also help growers and workers improve their knowledge of production, resource management and safe working practices.

Thus, sustainability should not be assessed only in terms of the resources entering and leaving the farm; it should also consider the people involved in the production process.

From more production to better production

The conventional question asked by a mushroom grower is often:

"How much mushroom did I produce?"

For a sustainable enterprise, a few more questions are equally important:

- ✓ How much did it cost to produce?
- ✓ How much energy and water did I use?
- ✓ How efficiently did I use my production capacity?
- ✓ How much of the crop was lost?
- ✓ What happened to my spent substrate?
- ✓ Did the enterprise generate adequate returns?
- ✓ Were workers provided with appropriate working conditions?

These questions shift the focus from simply producing more to producing better.

A Simple Sustainability Checklist for Mushroom Growers

Sustainability does not always require expensive technology. Improvements can begin with recording electricity and water use, maintaining insulation and equipment, reducing contamination and crop losses, identifying productive uses for spent substrate and maintaining records of production costs and returns.

ISSN: 3049-2289

For larger climate-controlled enterprises, improved environmental controls, energy-efficient technologies and renewable-energy options can offer additional opportunities. The appropriate intervention, however, will differ considerably between a small seasonal mushroom grower and a large climate-controlled button mushroom enterprise. Research comparing mushroom production systems also demonstrates that environmental performance varies with production technology, inputs and resource-use patterns (Jasińska, 2023; Goglio et al., 2024).

The Way Forward

The future of mushroom farming should not be judged by production alone. A sustainable mushroom farm should be able to remain economically viable, use resources efficiently, manage its residual materials responsibly and provide an appropriate working environment.

Mushroom cultivation already offers an important opportunity to transform lignocellulosic materials into food, while research on SMS demonstrates further possibilities for productive utilization of the material remaining after cultivation (Grimm and Wösten, 2018; Leong et al., 2022). For growers, sustainability can ultimately be understood in a simple way: obtaining greater and lasting value from the money, materials, energy, water and labour used on the farm.

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Mushrooms and the Indian consumers: Understanding the journey from curiosity to consumption

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Mushrooms have gradually moved from being a relatively unfamiliar food to an increasingly visible component of the Indian food basket. They are now available through vegetable markets, supermarkets, restaurants and an expanding range of processed and value-added food products. Nevertheless, mushroom consumption in India has not increased at the same pace as production and availability. Earlier studies have highlighted that mushrooms were yet to become a regular component of the diet of many Indian consumers and that consumer perceptions and purchasing behaviour were important for understanding the future of the mushroom sector (Shirur et al., 2014; Shirur et al., 2015).

The growth of mushroom production, therefore, does not automatically translate into regular consumption. The success of the mushroom sector ultimately depends on consumers, what they know about mushrooms, how they perceive them, where they purchase them, how they prepare them and whether they are willing to include them in their everyday meals. Understanding the consumer is therefore becoming as important as understanding mushroom production technology.

Why are consumers becoming interested in mushrooms?

Changing lifestyles are influencing food choices across India. Greater health awareness and interest in nutritious and diversified diets are encouraging consumers to explore alternatives to conventional food products (Kumar et al., 2022). Mushrooms fit naturally into this changing food environment. They provide protein, dietary fibre, vitamins, minerals and a range of biologically active compounds, while generally being low in fat and calories (Valverde et al., 2015). Their distinctive taste and texture also make them suitable for a wide variety of dishes (Jiang et al., 2023).

The nutritional and health-related properties of mushrooms have been widely documented, and their potential contribution to healthier diets has attracted increasing scientific and consumer interest (Valverde et al., 2015; Singh et al., 2022).

For consumers looking for healthier meals or greater variety in their diets, mushrooms can therefore be an attractive choice. However, nutritional value alone does not determine what people eat. Food choices are also influenced by familiarity, habits, taste preferences, purchasing conditions, price and psychological perceptions.

From knowing about mushrooms to eating mushrooms

There is an important difference between awareness and consumption. A person may know that mushrooms are nutritious but may still not purchase them regularly. Another consumer may enjoy mushrooms but purchase them only when they are easily available. Someone else may be interested in trying new varieties but may not know how to prepare them. This is why consumer behaviour needs to be viewed more broadly than simply asking whether people like mushrooms.

A study by Shirur et al. (2015) conceptualized mushroom consumer behaviour through five broad dimensions, viz., situational, dietary, economic, psychological and social factors, highlighting the multidimensional nature of mushroom consumption. Thus, the journey from awareness to consumption involves much more than simply knowing the nutritional benefits of mushrooms.

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Familiarity shapes food choices

Consumers generally feel more comfortable with foods that they have encountered repeatedly. In India, the button mushroom has become the most familiar cultivated mushroom for many consumers. Evidence from an Indian consumer study found white button mushroom to be the most preferred variety, followed by oyster mushroom and other varieties (Shirur et al., 2015). This creates both a challenge and an opportunity. Familiarity with one mushroom variety can provide an entry point for introducing consumers to a wider mushroom basket. Once consumers become comfortable purchasing and cooking mushrooms, they may be more willing to explore different varieties and mushroom-based products.

Research from other countries also suggests that mushroom consumers are not a homogeneous group. For example, Bringye et al. (2021) identified different consumer orientations towards mushrooms, including health-conscious consumers, highlighting the importance of understanding differences in consumer attitudes and motivations.

The recipe question

One of the simplest but often overlooked factors affecting food consumption is knowing what to do with the food once it reaches the kitchen. Consumers may hesitate to purchase mushrooms because they are uncertain about preparation methods, cooking time or suitable recipes. This is not merely a theoretical concern. In an Indian study, lack of knowledge about preparing different mushroom recipes was identified among the reasons associated with non-purchasing behaviour (Shirur et al., 2015).

Recipe demonstrations and simple preparation ideas may help consumers become more familiar with incorporating mushrooms into everyday meals. Research has shown that consumers' familiarity with foods and dishes is closely linked with their knowledge, preparation and consumption contexts (Frez-Muñoz et al., 2024). Mushrooms can be incorporated into curries, pulao, noodles, soups, sandwiches, flour-based products and snacks. The message is simple: knowing how to cook mushrooms can make them easier to include in everyday meals.

Health perception matters

Health is increasingly becoming an important consideration in food choices. Mushrooms are recognized for their nutritional properties and contain protein, fibre, vitamins, minerals and various bioactive compounds. Their nutritional composition and potential health-promoting properties have been extensively reviewed in the scientific literature (Valverde et al., 2015).

Health considerations also appear to influence mushroom consumption. In an Indian consumer study, good health and adding variety to the routine diet were among the important considerations reported for consuming mushrooms (Shirur et al., 2015). Similarly, consumer research in Hungary identified a health-conscious consumer orientation associated with mushroom consumption (Bringye et al., 2021). Communicating these benefits clearly can therefore help strengthen consumer interest. However, health communication needs to be practical rather than merely promotional. Consumers are more likely to relate to nutritional information when it is connected with everyday food choices.

Safety and trust

Food safety is another important component of consumer confidence (Grunert, 2005). The word “mushroom” can sometimes evoke concerns about poisonous or non-edible mushrooms, particularly among people with limited familiarity with the product. In the Indian consumer study by Shirur et al. (2015), fear regarding poisonous mushrooms was reported as one of the reasons associated with non-purchasing, although it was less prominent than issues such as availability and freshness. Clear information about cultivated edible mushrooms, safe handling, storage and preparation can help build consumer confidence. Reliable labelling and quality assurance can further strengthen trust, particularly as

ISSN: 3049-2289

the market expands to include processed and specialty mushroom products.

Availability can decide the purchase

Even a consumer who likes mushrooms cannot purchase them if they are difficult to find. Availability remains particularly important for products with a relatively limited consumption base. Evidence from India has shown that non-availability of mushrooms in local markets and lack of freshness were among the important reasons associated with non-purchasing behaviour (Shirur et al., 2015). Improved availability through supermarkets, local retailers, farmers' markets, direct marketing and other channels can therefore make mushrooms more accessible to consumers. This also highlights an important link between production and marketing. Increasing production without ensuring that mushrooms reach consumers in fresh and convenient forms may not be sufficient to expand demand.

Price and perceived value

Price is another factor influencing food choices. Consumers compare mushrooms with other vegetables and food products available to them. The decision to purchase therefore depends not only on the absolute price but also on whether consumers believe that the product provides sufficient value. The Indian evidence suggests that price is one of several economic considerations affecting mushroom purchasing behaviour (Shirur et al., 2015). At the same time, consumers also consider product characteristics such as colour, shape and size when making purchasing decisions. Nutrition, freshness, quality, convenience and taste can all contribute to perceived value. Value-added products may offer another opportunity by providing convenience and allowing mushrooms to reach consumers who may not regularly purchase fresh mushrooms.

From button mushroom to a diverse mushroom basket

The Indian mushroom market has considerable potential for diversification. While button mushroom remains familiar to many consumers, other cultivated mushrooms can provide new tastes, textures and nutritional experiences. Oyster, milky, shiitake and other specialty mushrooms offer opportunities to broaden consumer choice. However, diversification of production needs to be accompanied by diversification of consumer awareness.

Introducing consumers to new mushroom varieties through tasting programmes, food festivals, recipe demonstrations, social media, educational campaigns and retail displays can help reduce unfamiliarity. A diverse mushroom market will ultimately require a diverse consumer base that is willing to explore different varieties and forms of mushrooms.

The consumer at the centre of mushroom sector development

The future of India's mushroom sector will depend not only on how efficiently mushrooms can be produced, but also on how successfully they can be integrated into consumers' everyday lives. A consumer-centred mushroom sector must recognise that consumers differ in their familiarity, knowledge, confidence and willingness to experiment. Some may already be enthusiastic mushroom consumers, while others may require greater exposure, information or reassurance before making mushrooms a regular part of their diet.

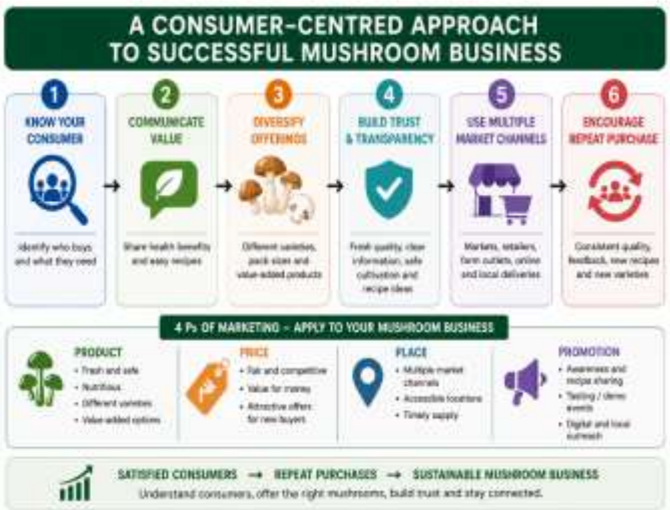

Fig. 1. Consumer-centred marketing strategies for mushroom business.

ISSN: 3049-2289

This makes consumer behaviour an important link between production and market development. Mushrooms have nutritional value, culinary versatility and considerable potential for diversification. The next step is to make these advantages meaningful to consumers. The journey from "I know about mushrooms" to "I buy mushrooms" and finally "I regularly eat mushrooms" requires awareness, accessibility, affordability, confidence and familiarity. Understanding this journey can help farmers, entrepreneurs, marketers, researchers and policymakers build a stronger and more consumer-responsive mushroom sector in India.

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The power of Refugia: A smart strategy for sustainable deworming

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Gastrointestinal parasitism is one of the major constraints affecting livestock productivity worldwide. Routine and frequent use of anthelmintics has contributed to the development of anthelmintic resistance, threatening the long-term effectiveness of available drugs (Kaplan & Vidyashankar, 2012; WOAH, 2021). Refugia management helps delay resistance by maintaining a population of drug-susceptible parasites that can dilute resistant genes (van Wyk, 2001; Kenyon et al., 2009). This approach can be combined with targeted selective treatment, fecal egg count monitoring, pasture management, and strategic deworming (Leathwick et al., 2006; Rose et al., 2020).

Introduction

Parasitic infections reduce productivity in cattle, buffaloes, sheep, goats, and other grazing animals by adversely affecting growth, feed utilization, milk production, fertility, and overall health (Charlier et al., 2009; Hoste et al., 2010).

Frequent and indiscriminate use of anthelmintics creates strong selection pressure. Susceptible parasites are eliminated, while resistant parasites survive and reproduce, gradually increasing the frequency of resistance alleles in the population (Kaplan & Vidyashankar, 2012; Kotze & Prichard, 2016).

Because the development of new anthelmintic compounds has been limited, preserving the efficacy of existing drugs is an important component of sustainable parasite control (Geary et al., 2012; WOAH, 2021).

What is refugia?

Refugia refers to the proportion of a parasite population that is not exposed to an anthelmintic treatment. It may include parasites in untreated animals, free-living stages on pasture, and parasites that are not reached by the treatment (van Wyk, 2001; Kenyon et al., 2009).

These susceptible parasites can reproduce with resistant parasites that survive treatment, thereby reducing the relative frequency of resistance in later generations (Leathwick et al., 2006; Martin et al., 1989).

How does anthelmintic resistance develop?

Parasite populations naturally contain genetic variation, including a small proportion of parasites with reduced susceptibility to particular drugs. Repeated treatment of the entire herd or flock removes susceptible parasites and gives resistant parasites a reproductive advantage (Kaplan & Vidyashankar, 2012; Kotze & Prichard, 2016).

As resistance increases, treatment efficacy declines, potentially resulting in treatment failures, production losses, and increased disease risk (WOAH, 2021).

How does refugia work?

Refugia-based strategies reduce selection pressure by maintaining a population of parasites that has not been exposed to the drug. Susceptible parasites from untreated animals or pasture can then dilute the resistant parasites surviving treatment (van Wyk, 2001; Kenyon et al., 2009).

However, refugia should be managed carefully because the appropriate strategy depends on parasite species, host age, climatic conditions, pasture contamination, drug class, and the local level of resistance (Gaba et al., 2010; Burgess et al., 2012).

Significance of refugia management

Maintaining susceptible parasites can delay the development of anthelmintic resistance and prolong the useful life of available drugs (Leathwick et al., 2006; Kenyon et al., 2009).

Targeted treatment also reduces unnecessary drug use. Recent evidence indicates that targeted selective treatment can substantially reduce anthelmintic use while maintaining acceptable animal performance when suitable selection criteria are applied (Rose et al., 2020).

Implementing refugia management

1. Targeted selective treatment

Instead of treating every animal, treatment should be directed toward animals most likely to benefit. Selection may be based on body condition, weight gain, anemia or mucous membrane color, clinical signs, productivity, and fecal egg count, depending on the species and production system (Leathwick et al., 2006; Kenyon et al., 2009).

Healthy animals should not automatically be treated solely because other animals in the group are receiving treatment. Nevertheless, treatment decisions should be made with veterinary guidance, particularly in young, pregnant, severely affected, or immunocompromised animals.

2. Fecal egg count monitoring

Fecal egg counts can help identify animals or groups with greater parasite burdens and can be used to monitor the effectiveness of treatment. The fecal egg count reduction test is widely used to investigate suspected anthelmintic resistance (Kaplan et al., 2023; WOAH, 2021).

Fecal egg counts should be interpreted alongside clinical findings, animal age, parasite species, and production conditions because egg counts do not always directly reflect the total worm burden or the severity of disease.

3. Strategic grazing management

Animals should not always be moved immediately to clean pasture after treatment. Moving recently treated animals onto uncontaminated pasture may increase the proportion of resistant larvae deposited on that pasture and accelerate resistance development (Kenyon et al., 2009; SCOPS, n.d.).

Pasture rotation, appropriate stocking density, mixed-species grazing, and planned use of safe pasture can reduce parasite transmission, although their effectiveness varies with climate, pasture conditions, and parasite biology (Hoste et al., 2010).

4. Nutrition

Adequate nutrition supports immune function and helps animals tolerate moderate parasite burdens. Nutritional management should complement, rather than replace, diagnosis and appropriate anthelmintic treatment (Hoste et al., 2010).

5. Quarantine of newly introduced animals

Newly purchased animals may introduce resistant parasite populations. They should therefore be isolated, assessed, and managed according to a veterinary quarantine protocol before joining the resident herd or flock (WOAH, 2021).

6. Judicious use of drug classes

Anthelmintic selection, dosing, and drug combinations should be based on veterinary advice, correct body weight, local resistance information, and treatment efficacy monitoring. Simply rotating drug classes without confirming efficacy may not prevent resistance, especially where cross-resistance already exists (Kotze & Prichard, 2016; WOAH, 2021).

Conclusion

Refugia management represents a shift from attempting to eliminate every parasite toward reducing parasite-associated disease while preserving drug susceptibility. When combined with targeted selective treatment, fecal egg count monitoring, appropriate grazing management, correct dosing, and veterinary oversight, it can help delay the emergence of anthelmintic resistance (Kenyon et al., 2009; Kaplan et al., 2023).

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Reimagining North Bihar's Blue-Green Economy: Wetland Value Chains as Catalysts for Regional Transformation

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North Bihar's wetlands have historically been perceived through the narrow lens of recurrent flooding, ecological vulnerability, and developmental distress. This article argues for a paradigm shift: from flood management to wetland-led economic transformation. Drawing upon the emerging framework of blue-green economy, it examines how five strategically significant wetland-linked sectors—makhana, fish drying, singhara, water hyacinth-based enterprise, and dry vegetable processing—can serve as engines of inclusive regional growth through value-chain integration. The paper contends that North Bihar's principal developmental challenge is not ecological limitation but systemic under-realization of value due to fragmented processing systems, weak market linkages, and inadequate institutional convergence. By repositioning wetlands as productive economic infrastructure rather than seasonal liabilities, North Bihar can unlock a resilient, regenerative, and locally anchored development model capable of generating sustainable livelihoods while strengthening ecological stewardship.

1. Introduction: Beyond the Flood Narrative

Every monsoon, North Bihar is transformed. Rivers spill across embankments; roads disappear beneath swollen currents; agricultural fields dissolve into temporary inland water bodies; and villages recalibrate their rhythms around the inevitability of inundation. For decades, this annual phenomenon has shaped public discourse, policy imagination, and developmental intervention in the region. North Bihar has largely been framed as a geography of crisis defined by floods, displacement, infrastructural fragility, and recurring economic uncertainty.

Yet this dominant narrative obscures a more profound reality. The very waters long regarded as developmental obstacles constitute one of India's most underleveraged ecological economic assets.

Spread across districts such as Darbhanga, Madhubani, Supaul, Saharsa, Katihar, Purnea, Araria and Kishanganj, North Bihar's vast network of wetlands, oxbow lakes, chaurs, seasonal ponds, and floodplain ecosystems sustains intricate livelihood systems developed over generations. These landscapes support aquatic cultivation, inland fisheries, wetland horticulture, biomass harvesting, and seasonal processing traditions that together form the foundation of an emerging blue-green rural economy.

The challenge confronting North Bihar is not resource scarcity. It is the systemic inability to convert ecological abundance into sustained economic value. If strategically integrated through modern value-chain architecture, five wetland-linked sectors—makhana, fish drying, singhara, water hyacinth enterprise, and dry vegetable processing—could redefine the developmental trajectory of the region.

2. Makhana: From Production Dominance to Value Ownership

Few products symbolize North Bihar's latent economic potential as powerfully as makhana (*Euryale ferox*). Often described as Bihar's "white gold," makhana has evolved from a traditional food item into a globally recognized functional superfood. Rich in protein, low in fat, naturally gluten-free, and increasingly marketed within wellness-oriented consumer segments, makhana now occupies a premium niche in domestic and international food markets. Bihar contributes the overwhelming majority of India's makhana production with the Mithila region serving as the epicenter of cultivation and processing.

This should, in principle, position North Bihar as a major beneficiary of the crop's expanding global demand. Yet the economic structure of the sector reveals a familiar paradox: production concentration does not automatically translate into value capture.

Makhana processing remains highly labor-intensive and technically specialized. The sequence—from seed cultivation and aquatic harvesting to roasting, tempering, popping, grading and packaging—requires precision and skill developed through inherited local expertise. However, producers often remain confined to the lower-value segments of the chain. Limited mechanization, fragmented aggregation systems, inconsistent grading standards, and dependence on intermediary traders significantly constrain farmer earnings. Much of the premium accrues downstream to processors, urban distributors, and branded retailers. The future of North Bihar's makhana economy depends on moving beyond cultivation dominance toward integrated value-chain ownership. Cluster-based processing units, farmer producer organizations, standardized quality certification, geographical branding, and diversified value-added products—including flavored snacks, nutritional flour, breakfast formulations, and export-oriented packaged products—could dramatically enhance local income retention. The market already recognizes makhana's value. The pressing question is whether North Bihar will capture it.

3. Fish Drying: Modernizing Traditional Protein Economies

Fish drying represents one of North Bihar's oldest adaptive responses to ecological seasonality.

For generations, fishing communities across floodplain regions have relied on drying as a practical means of preserving seasonal abundance, reducing perishability, and ensuring protein availability beyond peak catch periods. Despite its historical significance, this sector remains economically underdeveloped. Most fish drying operations continue to rely on open-air sun drying under inconsistent sanitary conditions. Exposure to dust, fluctuating humidity, insect contamination, and weather uncertainty compromises quality, reduces shelf life, and limits market reach. As a result, dried fish from North Bihar largely circulates within informal local markets characterized by low margins and minimal quality differentiation. This underdevelopment is particularly striking given robust regional demand for dried fish across Eastern and Northeast India as well as neighboring South Asian markets. The technological interventions required to modernize this sector are neither prohibitively expensive nor institutionally complex. Solar tunnel dryers, moisture-controlled curing systems, improved salting protocols, vacuum packaging, and collective processing infrastructure can substantially elevate quality and consistency. More importantly, modernization would reposition fish drying from subsistence preservation to enterprise-led protein processing. For women-led co-operatives and fisher collectives, this presents a viable pathway toward income diversification and market expansion. The constraint is not demand. It is infrastructural neglect.

4. Singhara: Unlocking Year-Round Market Potential

Singhara, or water chestnut, remains deeply embedded within North Bihar's wetland food systems. Widely consumed during seasonal harvest cycles and valued for its nutritional properties, the crop occupies an important place in regional diets and local commerce. Yet its economic potential remains significantly underrealized. The principal challenge lies in perishability. Fresh singhara deteriorates rapidly after harvest, compressing marketing windows and forcing producers into immediate sales. Seasonal market gluts depress prices, often compelling distress transactions that undermine producer profitability. This cycle traps the crop within low-value seasonal trade. Its processed form, however, offers far greater promise. Singhara flour is naturally gluten-free, nutritionally rich, and increasingly aligned with global consumer demand for specialty plant-based and alternative grain products. It holds substantial potential across wellness food, dietary supplement, and premium health-product segments. Realizing this opportunity requires localized processing infrastructure for drying, milling, packaging, storage, and quality standardization. Given the rapid expansion of health-conscious food consumption across urban India, North Bihar is strategically positioned to establish itself as a major supplier of the product. The challenge is not market relevance. It is organizational readiness.

5. Water Hyacinth: Circular Economy through Ecological Restoration

Few wetland resources better illustrate the intersection of ecological challenge and economic possibility than water hyacinth. Across North Bihar's water bodies, this invasive species obstructs waterways, reduces dissolved oxygen, impairs fisheries, and accelerates ecosystem degradation. Conventionally viewed as waste, it imposes substantial ecological and economic costs. Yet globally, water hyacinth has been successfully repurposed into a wide range of commercially viable products, including woven handicrafts, biodegradable packaging, furniture, paper, compost, and natural-fiber decor. For North Bihar, this represents an exceptional circular economy opportunity. Its harvesting simultaneously restores wetland functionality and generates raw material for enterprise. This dual ecological and economic benefit is especially relevant for women's self-help groups where low-capital craft-based production models can be rapidly scaled through targeted skill development. Growing urban demand for sustainable lifestyle products further strengthens commercial viability. What remains absent is ecosystem-level support: design innovation, technical capacity-building, branding assistance, and digital market access. Strategic partnerships between producer collectives, design institutions, and e-commerce platforms could convert this ecological burden into a regenerative enterprise system. This is not merely waste utilization. It is environmental restoration through economic design.

6. Dry Vegetable Processing: Converting Surplus into Stability

North Bihar's agricultural productivity frequently generates a paradox of abundance. During peak harvest seasons, vegetable oversupply depresses farmgate prices and contributes to significant post-harvest losses due to inadequate storage and weak market access. Dry vegetable processing offers a practical corrective. Through dehydration, producers can convert perishable surplus into shelf-stable, value-added products suitable for institutional kitchens, processed food manufacturers, retail supply chains, and emergency food systems. The process—washing, slicing, blanching, drying, packaging, and storage—is technologically accessible and highly adaptable to decentralized production models. Solar dehydration systems, in particular, offer cost-effective opportunities for community-level enterprise development. For women-led rural micro-enterprises and farmer producer organizations, this sector offers significant potential for income stabilization. However, adoption remains constrained by limited technical awareness, inconsistent packaging standards, food safety compliance barriers, and weak market intelligence. These are not structural impossibilities. They are solvable institutional deficits.

7. The Structural Bottleneck: Fragmented Value Chains

Across all five sectors, a common pattern emerges.

- North Bihar does not suffer from production deficiency.
- It suffers from value-chain fragmentation.
- Small producers remain disconnected from modern processing systems. Post-harvest losses erode margins. Financial products poorly reflect wetland-based livelihood realities. Institutional responsibilities remain scattered across multiple departments with limited convergence.

The result is predictable: A region rich in ecological capital remains poor in realized economic value.

8. Toward a Regional Blue-Green Development Framework

Transforming North Bihar's wetland economy requires more than isolated interventions. It demands a coherent regional strategy anchored in value-chain integration. Key priorities include:

- **Producer-owned processing infrastructure** to reduce intermediary dependence and strengthen local retention of value.
- **Dedicated enterprise finance mechanisms** tailored to aquatic and wetland-linked livelihoods.
- **Regional certification and branding systems** capable of accessing premium national and export markets.
- **Skill ecosystems** focused on quality assurance, entrepreneurship, packaging innovation, and digital commerce.
- **Institutional convergence** across agriculture, fisheries, MSME, and rural development departments.
- **Research-design-industry partnerships** connecting grassroots production systems with technological innovation.

The central objective must be straightforward: Ensure that value generated from North Bihar's wetlands remains within North Bihar.

Conclusion: The Future Hidden in Water

For too long, North Bihar's wetlands have been viewed primarily as symbols of vulnerability.

That perspective is no longer sufficient. These landscapes are not simply flood-prone geographies requiring management. They are productive ecological infrastructures capable of powering a new developmental model. Makhana, fish drying, singhara processing, water hyacinth enterprise, and dry vegetable value addition collectively offer more than livelihood diversification. They offer a blueprint for regional transformation rooted in resilience, regeneration, and local ownership. North Bihar's greatest developmental resource is not land alone. It is the water that defines it. Within these wetlands lies the possibility of a future where ecological stewardship and economic prosperity are not competing objectives, but mutually reinforcing realities. The next chapter of North Bihar's development may rise not despite its waters but because of them.

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Reprogramming the Rhizosphere: Microbiome Engineering as a Mechanistic Alternative to Synthetic Nitrogen Fertilization in Cereal Agriculture

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Nitrogen availability has functioned as the principal yield-limiting variable in cereal agriculture since the mid-twentieth century, and the Haber-Bosch synthesis of ammonia remains, by most accounts, the single technological intervention most responsible for sustaining human population growth over the past century. That dependence, however, carries a well-documented biological cost. Sustained synthetic nitrogen application measurably restructures the composition and functional capacity of the rhizosphere microbiome, the assemblage of bacteria, fungi, archaea, and protists occupying the narrow zone of soil adjacent to plant roots, generally reducing microbial diversity and suppressing taxa associated with nutrient cycling and pathogen suppression (Xun et al., 2024). This finding has reframed a substantial portion of current soil science: rather than treating the rhizosphere as an inert substrate to be supplemented with fertilizer, researchers increasingly treat it as a second, heritable genome whose composition can be deliberately engineered to reduce a crop's dependence on exogenous nitrogen input.

The mechanistic basis for this approach rests on a well-characterized set of plant growth-promoting rhizobacteria (PGPR) functions. Diazotrophic bacteria, including free-living and associative genera such as *Azospirillum* and *Azotobacter*, fix atmospheric dinitrogen into plant-available ammonium via the nitrogenase enzyme complex, while phosphate-solubilizing strains secrete organic acids that liberate mineral-bound phosphorus, and other PGPR taxa modulate root architecture through auxin and cytokinin signaling to increase the root surface area available for nutrient acquisition. A comprehensive review synthesizing 158 studies published between 1996 and 2024 documented that PGPR-based biofertilizers now target not only nitrogen and phosphorus but also potassium, sulfur, zinc, and iron acquisition, reflecting a broadening of the field beyond its original focus on macronutrient substitution (Alzate Zuluaga et al., 2024). In maize specifically, multi-omics analyses integrating metagenomic, metatranscriptomic, and metabolomic data have identified rhizosphere-resident taxa whose relative abundance correlates with host nitrogen-use efficiency (NUE) independent of soil nitrogen concentration, suggesting that the microbiome constitutes a heritable trait interacting with, rather than merely responding to, plant genotype (Luo et al., 2025).

Field-scale evidence, while more limited than the mechanistic literature, is accumulating in a directionally consistent manner. A randomized field trial in potato reduced inorganic fertilizer input by 50% while co-applying microbial inoculants containing *Azospirillum*, *Bacillus*, and *Pseudomonas* consortia, and reported that the combined treatment sustained both rhizosphere microbial diversity and tuber yield relative to full-rate conventional fertilization, indicating that microbial inoculation can substitute for a substantial fraction, though not the entirety, of synthetic nitrogen input under field conditions (Ollio et al., 2025). Parallel work engineering synthetic nitrogen-fixing consortia has extended the approach toward circularity: one 2025 study assembled a self-assembled nitrogen-fixing microbial community using atmospheric dinitrogen as the sole nitrogen source and volatile fatty acids derived from anaerobic digestion of swine waste as the carbon source, then demonstrated its efficacy as a biofertilizer in tomato, illustrating a pathway by which agricultural and livestock waste streams could be converted into biologically fixed nitrogen rather than processed through the energy-intensive Haber-Bosch route (Rodríguez-Romero et al., 2025). More recent bioengineering efforts have applied CRISPR-Cas-based multiplex editing to optimize metabolic pathways within candidate PGPR strains directly, including modification of *Pseudomonas* and *Corynebacterium* strains for enhanced phosphate solubilization, indicating convergence between microbiome science and the genome-editing methods more commonly associated with crop breeding itself (Adhikari et al., 2025).

These developments carry particular weight for India, whose agricultural nitrogen economy exhibits a degree of imbalance that is unusual even by global standards. The recommended nitrogen-phosphorus-potassium (N:P:K) application ratio for Indian soils is approximately 4:2:1, yet the ratio actually observed across many states now exceeds 10.9:4.1:1, a consequence of a subsidy structure that has kept the retail price of a 45-kilogram bag of urea fixed at roughly ₹242–267 since 2018 even as its actual cost of production and import has risen several-fold above that price (Rethinking India's Fertiliser Policy and Reforms, 2026; India's Fertilizer Reform, 2026). India's Economic Survey 2025-26 explicitly identified this pricing distortion as the principal driver of a deteriorating soil health profile, reporting that more than half of the roughly nine million soil samples tested nationally during the 2025-26 season showed low organic carbon content, and recommended raising the urea retail price while compensating farmers through direct Aadhaar-linked cash transfers rather than continuing to subsidize the input itself (Economic Survey 2025-26, 2026; Fertilizer Squeeze Report, 2026). The fiscal dimension of the problem is not marginal: India's total fertilizer subsidy for 2025-26 is projected at approximately ₹1.9 trillion, of which roughly ₹1.3 trillion is attributable to urea alone, a sum that now exceeds the country's entire agriculture budget and constrains public investment in irrigation and agricultural research (India's Soil Crisis, 2026). A 2025 University of Chicago-affiliated analysis of the 2010 Indian subsidy reform that further lowered relative nitrogen prices found a measurable increase in downstream nitrate pollution and, more strikingly, a 1.6% increase in rural infant mortality for every 1% increase in downstream nitrate concentration, a finding that extends the soil-health argument for reduced nitrogen dependence into an explicit public-health register (Hultgren, 2025).

The Government of India has already initiated a policy response oriented, at least in principle, toward the biological substitution pathway described above. The PM-PRANAM scheme (Prime Minister Programme for Restoration, Awareness, Nourishment and Amelioration of Mother Earth), approved by the Cabinet Committee on Economic Affairs, offers financial incentives to state governments that reduce chemical fertilizer consumption and promote alternatives including organic manure, compost, and biofertilizers, and has been accompanied by a ₹1,451 crore allocation for market development assistance targeting organic fertilizer produced from Gobardhan biogas plants (Cabinet Approves PM-PRANAM, 2023; Empowering India's Farmers, 2024). Independent convenings of soil scientists and agricultural economists, including a 2025 roundtable organized by the Indian Council for Research on International Economic Relations, have echoed the same conclusion reached in the international peer-reviewed literature: that indiscriminate urea application is degrading soil organic matter and contaminating groundwater at a scale that now threatens the long-term productive capacity of Indian agriculture, and that microbiome-based and organic alternatives warrant substantially greater research investment and extension support than they currently receive (Urea Overuse Threatens Soils, 2025).

It would nonetheless overstate the current state of the science to characterize microbial biofertilizers as a drop-in replacement for synthetic nitrogen at the scale India's cereal system requires. The reviewed literature consistently notes that inoculant performance is highly context-dependent, varying with soil type, indigenous microbial community composition, and the degree to which introduced strains are adapted to a given crop's root exudate profile, with successful establishment more likely when candidate PGPR strains are isolated from the rhizosphere of the same crop species they are intended to inoculate (Herrero et al., 2025). Delivery formulation, strain viability during storage and transport, and the absence of standardized field protocols across the range of soil-climate conditions found across Indian agroecological zones remain unresolved logistical constraints rather than solved engineering problems (Alzate Zuluaga et al., 2024). The field-scale trials available to date, including the potato study cited above, achieved partial rather than complete nitrogen substitution, generally in the range of a 50% reduction in synthetic input while maintaining yield, which represents a meaningful but incomplete solution relative to the scale of India's nitrogen-use imbalance (Ollio et al., 2025).

Taken together, the mechanistic, field-scale, and policy evidence converge on a consistent conclusion: rhizosphere microbiome management constitutes a scientifically substantiated and increasingly tractable complement to, rather than a wholesale replacement for, synthetic nitrogen fertilization, and its adoption in India is now as much a question of subsidy design and extension infrastructure as it is a question of microbial ecology. Whether the current policy shift toward direct cash transfers and biofertilizer incentives translates into altered farmer behavior at the scale required to correct a 10.9:4.1:1 nutrient ratio will depend on the coming several agricultural seasons, and on whether the research base documented here can be translated into inoculant products robust enough to perform reliably across India's considerable agroecological diversity.

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Biomass Resources as Feedstocks for Biochar: From Waste to Value

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Biochar is a carbon-rich, porous solid material produced through the thermochemical conversion of biomass under limited or oxygen-deficient conditions, mainly by pyrolysis. It has attracted considerable attention as a sustainable soil amendment, carbon-sequestration material, and value-added product for agricultural and environmental applications. The properties of biochar depend strongly on the type of feedstock, its chemical composition, moisture content, particle size, and pyrolysis conditions. A wide variety of agricultural residues, forestry biomass, animal wastes, agro-industrial by-products, and other organic materials can be used for biochar production. Crop residues such as rice straw, wheat straw, maize stover, cotton stalks, soybean residues, and sugarcane bagasse are abundant resources, while woody biomass, coconut shells, cashew residues, fruit-processing wastes, and animal manures provide additional feedstock options. Selection of suitable biomass is important because feedstock characteristics influence biochar yield, pH, ash content, surface area, stability, and nutrient availability. This article discusses major biomass resources suitable for biochar production, their characteristics, advantages, limitations, and potential applications.

Introduction

The increasing generation of agricultural and agro-industrial residues has created significant challenges related to waste management, air pollution, and resource conservation. In many agricultural regions, crop residues are burned in the field, resulting in the emission of particulate matter and greenhouse gases. At the same time, these residues contain substantial amounts of carbon, energy, minerals, and organic compounds that can be recovered through appropriate conversion technologies. Biochar provides an opportunity to convert biomass residues into a stable, carbon-rich material. It is generally produced by heating biomass at approximately 300–700°C under limited oxygen supply. The process is commonly known as pyrolysis. Depending on the operating conditions, pyrolysis produces three major products: biochar, bio-oil, and producer/syngas. Biochar is the solid fraction and can be used in agriculture, environmental remediation, carbon management, and several industrial applications.

The suitability of biomass for biochar production depends on its cellulose, hemicellulose, lignin, ash, mineral and moisture contents. Lignin-rich feedstocks, particularly woody materials, generally produce more stable and carbon-rich biochars. Agricultural residues with higher ash and mineral content may produce biochars with relatively high pH and nutrient contents. The utilization of locally available biomass for biochar production can support a circular bioeconomy by converting low-value residues into useful products. It can also provide additional income opportunities for farmers and agro-processing industries.

Major Resources for Biochar Production

Biomass resources suitable for biochar production can broadly be classified into the following groups:

1. Agricultural crop residues
2. Forestry and woody biomass
3. Agro-industrial residues
4. Fruit and vegetable processing residues

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5. Animal manure and livestock residues
6. Aquatic and wetland biomass
7. Municipal and other organic biomass
8. Dedicated energy crops and invasive plant biomass

Agricultural Crop Residues

Agricultural residues are among the most abundant, renewable, and readily available feedstocks for biochar production. These residues are generated during harvesting, threshing, processing, and post-harvest operations and include rice straw and husk, wheat straw, maize stalks and cobs, soybean stalks, cotton stalks, pigeon pea and chickpea residues, groundnut shells, sugarcane trash, mustard and sunflower stalks, sorghum stalks, and millet residues. Rice husk is particularly valuable because of its high silica content, which becomes concentrated in the resulting biochar and can enhance its suitability for soil amendment and silica-related applications. Rice straw can also be converted into biochar rather than being openly burned, although its relatively high ash content and low bulk density need to be considered during handling and reactor design. Similarly, wheat straw contains cellulose, hemicellulose, and lignin and can produce useful biochar through slow pyrolysis. Maize cobs, stalks, leaves, and husks are also suitable feedstocks, with maize cobs being attractive due to their comparatively low moisture content and ease of handling. Cotton stalks, being lignocellulosic and relatively carbon-rich, can be chipped and pyrolyzed to produce biochar with considerable fixed carbon and potential applications in soil improvement and carbon sequestration.

The use of agricultural residues for biochar production offers several environmental, economic, and agricultural benefits. These materials are generally renewable, locally available, and relatively inexpensive, while their conversion into biochar can reduce open-field residue burning and provide an opportunity to transform low-value agricultural waste into a valuable soil amendment. Biochar derived from these residues may contribute to improved soil structure, water retention, nutrient-use efficiency, and long-term carbon storage. However, several limitations need to be addressed, including seasonal availability, high moisture content in some residues, variable and sometimes high ash content, low bulk density, and transportation and storage requirements. Therefore, proper collection, drying, size reduction, storage, and feedstock selection are essential for efficient and economically viable biochar production from agricultural residues.

Forestry and Woody Biomass

Forestry and woody residues are considered excellent feedstocks for biochar production because wood generally contains a high proportion of lignin, which contributes to the formation of stable, carbon-rich biochar. Major woody resources include sawdust, wood chips, bark, branches, tree prunings, forestry residues, bamboo, coconut wood, and timber-processing waste. Compared with many herbaceous agricultural residues, woody biomass generally produces biochar with higher fixed carbon and relatively lower ash content. Such biochar is often more stable in soil and can persist for longer periods, making it particularly attractive for carbon sequestration and long-term soil carbon management. Among these resources, sawdust is especially convenient for biochar production because

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of its relatively uniform particle size and low requirement for preprocessing, making it suitable for continuous pyrolysis systems.

Woody biomass offers several advantages, including high carbon and lignin content, relatively low ash content, good biochar stability, and suitability for continuous pyrolysis processes. However, its utilization also has certain limitations. Wood and woody residues may have competing uses in industries such as construction, fuel, paper, and animal bedding; therefore, biochar production should preferably utilize waste and residues that have limited alternative value. Sustainable sourcing is also essential to avoid encouraging deforestation or unsustainable biomass harvesting. Furthermore, treated, painted, or chemically preserved wood should generally be avoided because it may introduce harmful chemicals or contaminants into the biochar. Availability can also vary geographically depending on forestry activities and timber-processing industries.


Agro-Industrial Residues

Agro-industrial processing generates large quantities of residues that offer significant potential as feedstocks for biochar production. These materials are particularly attractive because they are often generated and accumulated at centralized processing facilities, which can reduce collection, handling, and transportation costs. Important agro-industrial residues include sugarcane bagasse and trash, coconut shell and husk, groundnut shell, cashew nut shell, oilseed cakes, coffee husk and pulp, tea waste, fruit-processing residues, and distillery residues. Among these, sugarcane bagasse is the fibrous residue remaining after juice extraction and is an important feedstock because of its high availability and lignocellulosic composition. Bagasse-derived biochar can contain considerable fixed carbon and has potential applications in soil improvement, wastewater treatment, and carbon sequestration. Similarly, coconut shells and husks can be converted into carbon-rich biochar, while coconut-shell biochar may develop a relatively high surface area under suitable pyrolysis or activation conditions. Groundnut shells are another promising resource because they are widely available, relatively easy to handle after drying, and can be converted into biochar for applications such as soil amendment and adsorption.

Cashew nut shells and other cashew-processing residues are particularly important agro-industrial feedstocks in cashew-producing regions. Cashew nut shells contain considerable energy and carbon and can be thermochemically converted into biochar; however, appropriate process management is necessary because they contain cashew nut shell liquid (CNSL) and associated phenolic compounds. In addition to shells, cashew apple pomace, generated as a by-product during juice extraction, represents a promising biomass resource containing organic matter and nutrients. Its conversion into biochar can reduce waste-disposal problems while recovering valuable carbon and nutrients. Overall, the utilization of agro-industrial residues for biochar production provides an effective approach for waste valorization, resource recovery, carbon sequestration, and development of a circular bioeconomy, particularly when locally available residues with limited alternative uses are prioritized.


Fruit and Vegetable Processing Residues

Fruit and vegetable processing industries generate substantial quantities of peels, seeds, pulp, pomace,

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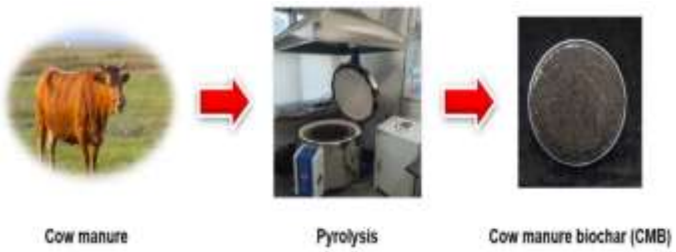
and other organic residues, which represent promising feedstocks for biochar production. Potential resources include mango peel and seed, banana residues, orange and citrus peels, apple pomace, pineapple residues, tomato-processing waste, grape pomace, cashew apple pomace, and vegetable-processing waste. These materials contain considerable amounts of organic matter and can be converted into biochar through suitable thermochemical processes. However, fruit and vegetable residues generally have high moisture content, making drying an important preprocessing step before pyrolysis. Proper drying can reduce energy requirements, improve thermal efficiency, and facilitate stable feeding into pyrolysis equipment. The chemical composition of these residues differs considerably from woody biomass; therefore, the yield and properties of the resulting biochar may also vary depending on the feedstock and processing conditions.

Biochar produced from fruit and vegetable residues can contain appreciable amounts of potassium, calcium, magnesium, and other mineral nutrients, which may enhance its potential as a nutrient-containing soil amendment. Such biochar can contribute to nutrient management, soil conditioning, and carbon storage while simultaneously reducing the environmental problems associated with disposal of food-processing wastes. However, fresh fruit and vegetable residues should generally not be directly introduced into conventional pyrolysis systems without adequate drying because their high moisture content increases energy consumption and may reduce overall process efficiency. Therefore, drying, size reduction, proper storage, and characterization of the feedstock are important steps for efficient conversion of fruit and vegetable residues into high-quality biochar.

Animal Manure and Livestock Residues

Animal manure is an important and readily available feedstock for biochar production and includes cattle dung, poultry litter, pig manure, goat and sheep manure, dairy-farm residues, and poultry bedding materials. Compared with woody biomass, manure-derived biochars generally contain higher ash and nutrient contents, including appreciable amounts of nitrogen, phosphorus, potassium, calcium, and magnesium, making them potentially useful as soil amendments, particularly in soils with low nutrient availability and poor fertility. The conversion of manure into biochar can also provide an effective method of livestock-waste management, reduce odor and waste-disposal problems, and recover nutrients in a more stable form. However, the suitability of manure as a biochar feedstock depends on its source and composition, as it may contain high moisture, salts, pathogens, antibiotics, and heavy metals. Therefore, proper feedstock characterization, drying, and controlled thermal treatment are essential to ensure the production of safe and high-quality biochar. Despite these limitations, manure offers significant potential for nutrient recycling, soil fertility improvement, waste management, and sustainable agricultural production.



The quality and characteristics of biochar are influenced by both the feedstock properties and pyrolysis conditions. The relative proportions of cellulose, hemicellulose, and lignin affect biochar yield, carbon content, and stability, with lignin-rich biomass generally producing more stable and carbon-rich biochar. Feedstock moisture is also important because high moisture increases the energy requirement for pyrolysis; therefore, proper drying can improve thermal efficiency and process stability. Pyrolysis temperature has a major influence on biochar properties. Lower temperatures generally result in higher biochar yield and greater retention of volatile compounds, whereas higher temperatures usually produce lower solid yields but greater carbonization, aromaticity, and carbon stability. Biochar is commonly produced within a temperature range of approximately 300–700°C, depending on the feedstock and desired properties. Residence time and heating rate also influence the final product; longer residence times generally increase carbonization, while slow pyrolysis is preferred when maximizing biochar production, whereas fast pyrolysis favors liquid products such as bio-oil.

Selection of a suitable biomass feedstock is essential for efficient and sustainable biochar production. An ideal feedstock should be abundant, inexpensive, locally available, relatively dry, carbon-rich, suitably lignified, free from contaminants, easy to transport and store, and have limited competing uses. Energy density and bulk density should also be considered when designing biomass collection, transportation, storage, and feeding systems. For agricultural applications, the produced biochar should be properly characterized for important properties such as pH, electrical conductivity, organic carbon, total carbon, ash content, fixed carbon, volatile matter, cation exchange capacity, surface area, pore structure, nutrient composition, and potentially toxic elements. Such characterization helps determine the suitability of biochar for specific applications and ensures that it can be safely and effectively used as a soil amendment or for environmental purposes.

The conversion of biomass residues into biochar provides significant environmental, agricultural, and economic benefits. Biochar contains relatively stable forms of carbon that decompose more slowly than untreated biomass, allowing it to contribute to long-term carbon storage and climate-change mitigation. Converting agricultural residues into biochar can also reduce open-field burning and associated air pollution while providing an alternative pathway for managing agricultural, forestry, livestock, and agro-industrial wastes. When appropriately produced and applied, biochar can improve soil structure, water-holding capacity, nutrient retention, and microbial habitat, although its effects depend on soil type, feedstock, pyrolysis conditions, and application rate. Furthermore, small-scale and decentralized pyrolysis systems can create value from locally available biomass, generate rural employment, and provide additional income opportunities for farmers, thereby supporting the development of a circular bioeconomy.

7. Conclusion

A wide range of biomass resources can be used for biochar production, including agricultural residues, forestry biomass, agro-industrial wastes, fruit-processing residues, animal manure, aquatic biomass and dedicated energy crops. Agricultural and agro-industrial residues are particularly promising because they are abundant, renewable and often have limited economic value. The selection of feedstock should be based on its availability, moisture content, chemical composition, ash content, energy value, transportation requirements and intended biochar application. Woody biomass generally produces stable, carbon-rich biochar, while crop residues and animal manure can produce biochars with higher nutrient and mineral contents. Fruit and aquatic residues can also provide useful feedstocks, although their high moisture content requires efficient drying. For sustainable biochar production, locally available

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residues with minimal competing uses should be prioritized. Proper feedstock selection combined with suitable pyrolysis conditions can convert agricultural and agro-industrial waste into a valuable product for soil management, environmental remediation, carbon sequestration and the development of a circular bioeconomy.

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Plant Health Management for Sustainable Agriculture: Integrating Soil Health, Biological Control, Natural and Organic Farming, Bioinoculants and Climate-Smart Practices

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Plant health is fundamental to sustainable agricultural production, food security and resilient farmer livelihoods, but it is increasingly threatened by insect pests, plant pathogens, declining soil health, nutrient imbalance, water stress and climatic variability. Excessive dependence on synthetic pesticides can contribute to resistance, residues, environmental contamination and disruption of beneficial organisms. Plant Health Management (PHM) therefore promotes a preventive, ecological and integrated approach that considers the plant, soil, microorganisms, pests and climate as an interconnected system. This article reviews major components of sustainable PHM, including soil health, balanced nutrition, organic amendments, bioinoculants, biological control, natural and organic farming, biochar, crop diversification and climate-smart agriculture. Beneficial microorganisms such as *Trichoderma*, *Pseudomonas* and *Bacillus* suppress pathogens through competition, antibiosis, mycoparasitism, lytic enzyme production and induced plant defence. Organic amendments such as compost and vermicompost can improve microbial activity, nutrient cycling and soil health, while biochar may modify soil properties and provide favourable niches for beneficial microorganisms. Biochar-microbial inoculant and compost/vermicompost-microbial combinations offer promising opportunities for improving rhizosphere colonization and disease suppression, although their performance remains dependent on soil, crop, microbial strain and environmental conditions. Natural-farming practices such as mulching, crop diversification and botanical preparations can complement scientifically validated IPM. Climate-smart practices, including resilient varieties, efficient water management, conservation agriculture and weather-based decision-making, further strengthen crop resilience. Research and technologies developed by Assam Agricultural University (AAU), including *Pseudomonas fluorescens*-based Biofor-Pf and *Trichoderma*-based biocontrol approaches, demonstrate the potential of locally adapted biological technologies. An integrated PHM framework combining ecological practices, biological control, scientific IPM and climate-smart technologies can reduce unnecessary chemical dependence while improving soil health, biodiversity, resource-use efficiency and resilience of agricultural systems, particularly in Assam.

Introduction

Plant health refers to the overall condition and functioning of plants, enabling them to grow, reproduce and perform their ecological and agricultural functions. It is closely associated with soil quality, nutrient availability, beneficial microorganisms, climatic conditions, crop genetics and management practices (Usharani *et al.*, 2019). Healthy plants form the foundation of agricultural productivity because they are better able to utilize nutrients and water, withstand environmental stresses and produce stable yields. However, plant health is increasingly threatened by insect pests, fungal and bacterial pathogens, nematodes, weeds, nutrient disorders, soil degradation and climatic extremes. Plant diseases are particularly important constraints to agricultural production. Fungal pathogens cause many economically important diseases, including wilt, root rot, damping-off, blight, anthracnose, rusts and post-harvest diseases. In addition to direct yield reduction, diseases can reduce product quality, marketability and storage life. Climate variability can further influence pathogen survival, host susceptibility and disease epidemics. Increasing temperature, altered rainfall, high humidity, flooding and drought may change the geographical distribution and epidemiology of pests and pathogens. The conventional response to these problems has often been the repeated application of synthetic pesticides. Although chemical pesticides remain valuable tools when used correctly, their excessive or indiscriminate application can contribute to pesticide resistance, residues, environmental contamination and adverse effects on pollinators, natural enemies and other beneficial organisms. FAO therefore promotes integrated pest management (IPM), in which preventive, biological, cultural, physical and chemical approaches are combined and pesticides are used only when economically and environmentally justified (FAO, 2017, 2020).

Plant Health Management extends this concept further by considering the plant, soil, microorganisms, pests, climate and management practices as one interconnected system. Rather than focusing only on eliminating a pathogen after disease development, PHM aims to create conditions in which plants remain vigorous and agroecosystems become less favourable to pest and pathogen establishment. This approach is especially relevant to Assam, where agricultural systems experience excess rainfall, flooding, waterlogging, erosion, dry spells, declining soil fertility and other climate-related stresses.

Concept and Principles of Plant Health Management

Plant Health Management should not be equated simply with the absence of visible disease. A healthy crop possesses a vigorous root system, balanced nutrition, adequate moisture, suitable soil structure, active rhizosphere microorganisms and genetic capacity to tolerate important biotic and abiotic stresses. The plant should also be capable of recovering from environmental stress and maintaining productivity under variable conditions. The central principle of PHM is therefore a transition from "killing the pathogen" to "building a healthy and disease-suppressive agroecosystem." Soil microbial communities are particularly important in this transition because beneficial microorganisms can compete with pathogens, produce antimicrobial substances and stimulate plant defence (Raaijmakers *et al*., 2009; Raghuvanshi *et al*., 2025). The major principles include prevention rather than cure, use of healthy planting material, maintenance of soil health, balanced nutrition, conservation of beneficial organisms, biological and ecological pest regulation, regular monitoring and early diagnosis, crop and genetic diversification, climate-risk management and judicious use of chemical pesticides. These principles are consistent with the ecosystem-based approach promoted under IPM (FAO, 2017, 2020).

Preventive management begins with healthy seed and planting material, disease-free nursery stock, resistant or tolerant varieties, crop rotation, sanitation and appropriate planting time. Resistant varieties are particularly important because they can reduce disease pressure without repeated pesticide application. Crop diversification and rotation also interrupt pest and pathogen cycles and improve agroecosystem stability. Regular monitoring is essential because the presence of a pest does not always mean that pesticide application is necessary. Field scouting, disease diagnosis, weather information and economic-threshold-based decisions allow interventions to be made at the appropriate time. Thus, PHM combines preventive management with early detection and need-based intervention.

Healthy Soil: The Foundation of Plant Health

Soil is a living ecosystem containing minerals, organic matter, water, air and an enormous diversity of microorganisms. Soil physical, chemical and biological properties influence root development, nutrient uptake, plant vigour and disease development. Healthy soils may become naturally disease suppressive, where microbial competition and antagonism restrict pathogen establishment and development (Raghuvanshi *et al*., 2025). Important soil-health practices include soil testing, balanced fertilization, application of farmyard manure (FYM), compost and vermicompost, green manuring, crop-residue recycling, biofertilizers, biochar, crop rotation, cover crops, moisture conservation and reduced unnecessary soil disturbance. Organic amendments can stimulate microbial biomass and activity and improve plant nutrient uptake. In a greenhouse experiment, Malik *et al*. (2013) reported that FYM, poultry litter and biogenic waste compost increased microbial biomass C, N and P, dehydrogenase activity, plant growth and nutrient uptake in wheat.

Cover crops and green manures provide additional benefits by protecting soil against erosion, conserving moisture and contributing organic residues to the soil. They can also influence microbial activity and provide habitat and resources for beneficial organisms (Hartwig & Ammon, 2002). Organic amendments may also contribute directly to disease suppression. They can modify soil microbial communities, improve microbial competition and create conditions unfavourable to soil-borne pathogens. Research on bio-organic fertilizers has demonstrated suppression of diseases such as Fusarium wilt through changes in soil microbial communities (Zhang *et al*., 2008). The soil microbiome therefore becomes an important component of plant health. Beneficial organisms such as *Trichoderma*, *Pseudomonas*, *Bacillus*, *Streptomyces* and arbuscular mycorrhizal fungi can contribute to pathogen suppression through competition, antibiosis, nutrient acquisition, enzyme production and stimulation of plant defence.

Balanced Plant Nutrition and Plant Health

Plant nutrition and disease susceptibility are closely interconnected. Nutrient deficiency can weaken plants and impair physiological and defence processes, while excessive application of particular nutrients may increase susceptibility to some pathogens and insect pests. Therefore, sustainable plant health requires balanced and soil-test-based nutrient management rather than indiscriminate fertilizer use. Integrated nutrient management combines mineral fertilizers with organic manures, composts, crop residues and biofertilizers. Organic amendments contribute carbon and nutrients and stimulate microbial activity, while fertilizers supply nutrients in quantities required by crops. Malik *et al*. (2013) demonstrated that organic amendments can increase microbial biomass and nutrient uptake, supporting the role of integrated nutrient management in improving plant growth. Biofertilizers containing nitrogen-fixing, phosphate-solubilizing, potassium-mobilizing and other beneficial microorganisms can complement nutrient management. Their effectiveness depends on integrating biological nutrient cycling with organic and mineral nutrient sources.

Role of Beneficial Microorganisms and Bioinoculants

Bioinoculants are preparations containing beneficial microorganisms introduced into the seed, soil, rhizosphere or plant environment to improve nutrient availability, plant growth or biological suppression of pests and pathogens. Important groups include *Trichoderma*, *Pseudomonas*, *Bacillus*, mycorrhizal fungi and other plant-growth-promoting microorganisms.

Beneficial microorganisms can colonize roots and occupy ecological niches that might otherwise be available to pathogens. They may also compete for nutrients such as iron through siderophore production, produce antimicrobial compounds and stimulate plant defence responses. The rhizosphere can therefore act as a biological "battlefield" where beneficial and pathogenic microorganisms compete for space and resources (Raaijmakers *et al*., 2009).

A major advantage of microbial bioinoculants such as *Trichoderma* is their ability to employ multiple modes of action. *Trichoderma* spp. can suppress plant pathogens through mycoparasitism, competition and antibiosis, while also inducing systemic resistance,

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enhancing nutrient uptake and promoting plant growth. They also produce a wide range of extracellular enzymes, antimicrobial compounds and defence-related substances. However, successful application under field conditions depends on effective strain selection, viable propagules, appropriate formulation and delivery systems. The efficacy of *Trichoderma* may also vary with environmental and soil conditions, including soil organic matter, pH, nutrient availability and moisture. Therefore, field validation and the selection of strains adapted to specific crops and agroecological conditions are essential for reliable disease management (Dutta *et al*., 2022).

Trichoderma, _Pseudomonas_ and _Bacillus_ as Important Biocontrol Agents

Among microbial biocontrol agents, *Trichoderma*, *Pseudomonas* and *Bacillus* are particularly important because of their diverse mechanisms and adaptability to different crops. *Trichoderma* species are widely studied for the management of soil-borne diseases, including Fusarium wilt, damping-off and root rot caused by *Fusarium*, *Rhizoctonia* and *Pythium* spp., as well as diseases caused by *Sclerotium* and *Macrophomina*. Their mechanisms include mycoparasitism, antibiosis, competition and enzyme production (Sood *et al*., 2020). *Pseudomonas fluorescens* and related species colonize the rhizosphere and produce antibiotics, siderophores and other metabolites. They have been evaluated against bacterial wilt caused by *Ralstonia solanacearum*, Fusarium wilt, damping-off and other soil-borne diseases, while their ability to combine rhizosphere colonization, nutrient competition, antimicrobial activity and induced resistance makes them valuable biological control agents. *Bacillus* species have an additional practical advantage because their endospores provide greater tolerance during formulation and storage. *Bacillus subtilis* and related species can produce lipopeptides with antifungal properties and can contribute to the suppression of Fusarium, Rhizoctonia, Pythium and Sclerotium diseases, besides promoting plant growth (Raghuvanshi *et al*., 2025). The use of microbial consortia combining compatible microorganisms is another emerging approach. A consortium may provide complementary functions, for example, one organism providing pathogen antagonism while another promotes nutrient acquisition or plant growth. However, compatibility between microorganisms and stability of the formulation must be established before field-scale use. Research on biological plant disease management has demonstrated the potential of beneficial microorganisms such as *Pseudomonas fluorescens*, *Trichoderma* spp. and *Bacillus* spp. for sustainable crop protection. Among the microbial biocontrol products, Biofor-Pf, based on *Pseudomonas fluorescens*, has been evaluated for the management of bacterial wilt caused by *Ralstonia solanacearum*, while vermicompost-based Biofor-Pf has shown promise in enhancing disease suppression through the combined effects of microbial antagonism and organic amendment (Bora & Deka, 2010). Similarly, *Trichoderma* spp. have been widely investigated for the suppression of soil-borne pathogens and promotion of plant growth through competition, antibiosis, mycoparasitism and induction of plant defence responses (Sood *et al*., 2020). Biofor-Pf-2, containing *P. fluorescens* and *Trichoderma harzianum*, and Biozin-PTB, containing *Pseudomonas*, *Trichoderma* and *Bacillus*, represent examples of microbial formulations designed for the management of fungal and bacterial soil-borne pathogens. In addition, biocontrol products based on entomopathogenic fungi such as *Metarhizium anisopliae* and *Beauveria bassiana* provide biological options for managing insect pests including white grubs, termites, beetles, aphids, whiteflies, thrips and certain caterpillars. Studies evaluating commercial *P. fluorescens*-based biopesticides have also demonstrated their potential against important phytopathogens (Rahman *et al*., 2020). Collectively, these biocontrol products demonstrate how microbial antagonists, either individually or in combination with organic carriers such as compost and vermicompost, can contribute to biologically active and disease-suppressive agroecosystems while reducing dependence on synthetic pesticides.

Natural Farming Inputs and Practices for Plant Health Management

Natural farming emphasizes the use of locally available biological resources, ecological processes and reduced dependence on synthetic external inputs. From a plant-health perspective, natural farming seeks to maintain healthy crops through soil biological activity, crop diversification, ecological engineering, mulching, botanical preparations, biological control, healthy planting material and improved nutrient cycling. Important natural-farming practices and preparations include Beejamrit, Jeevamrit, Panchagavya, Whapasa, Achhadana, Neemastra, Brahmastra and Agniastra. These practices are primarily preventive and ecological in nature and are most appropriately integrated with scientifically validated Integrated Pest Management (IPM) strategies.

Natural farming uses locally available biological resources to support soil health, nutrient cycling and ecological pest management. Beejamrit is commonly prepared with 5 kg fresh cow dung, 5 L cow urine, 50 g lime and 20 L water, with a handful of soil from the farm bund or biologically active area; it is used for seed or planting-material treatment. Jeevamrit generally contains 10 kg fresh cow dung, 5–10 L cow urine, 1–2 kg jaggery, 1–2 kg pulse flour and a handful of soil in 200 L water, fermented for several days and applied to soil or through irrigation. Panchagavya is commonly prepared using 5 kg cow dung, 3 L cow urine, 2 L milk, 2 L curd and 1 L ghee, with some formulations additionally incorporating jaggery or banana; after fermentation it is diluted and used as a foliar or soil application. Whapasa is a soil-water management principle rather than a specific preparation, emphasizing adequate moisture and air around the root zone, while Achhadana refers to mulching with straw, crop residues, leaves or grasses to conserve moisture, moderate soil temperature, suppress weeds and reduce erosion and pathogen splash.

For pest management, Neemastra is commonly prepared using 5 kg crushed neem leaves, 5 L cow urine, 5 kg cow dung and 100 L water, fermented for about 24 hours, filtered and sprayed. Brahmastra is commonly prepared from 3 kg crushed neem leaves mixed with 10 L cow urine, along with approximately 2 kg each of custard-apple, papaya, pomegranate and guava leaves, which are processed with water, boiled and extracted before use. Agniastra has several formulations; a commonly described preparation uses 5 kg neem leaves, 1 kg tobacco, 500 g green chilli, 500 g garlic and 10 L cow urine, with the ingredients processed/boiled and the extract diluted before spraying. Other botanical preparations include neem, chilli-garlic and other pesticidal plant extracts. Because these farmer-prepared formulations are not standardized, the actual concentration, dilution and application dose should be adjusted according to crop, pest, formulation and phytotoxicity risk, and they are best used as supplementary components of an integrated pest-management programme.

Organic Farming and Plant Health

Organic farming aims to maintain agricultural production through ecological processes and restricted use of synthetic inputs. For plant health, important organic practices include crop rotation, organic manures, compost, vermicompost, green manuring, biological pest management, resistant varieties and cultural practices. Organic matter plays a central role because it improves soil structure, nutrient cycling and microbial activity. Malik *et al.* (2013) demonstrated that organic amendments increased microbial biomass and nutrient uptake in wheat. Organic amendments may also create disease-suppressive conditions by stimulating beneficial microbial populations and altering the physical and chemical environment of pathogens. However, organic farming should not be equated with the complete absence of crop protection. Organic systems can experience significant pest and disease pressure, particularly under monocropping or poorly managed conditions. Consequently, organic IPM, based on resistant varieties, crop rotation, sanitation, biological control, botanical products, monitoring and other preventive measures, is essential.

Biochar, Compost, Vermicompost and Microbial Inoculants in Disease Suppression

Biochar is a carbon-rich material produced through the thermal conversion of biomass under limited oxygen. It has attracted considerable interest as a soil amendment because of its potential to improve soil structure, nutrient retention, water-holding capacity and carbon sequestration. Increasing evidence suggests that biochar can contribute to plant disease suppression by modifying soil physicochemical properties, influencing rhizosphere microbial communities, sorbing pathogen-derived or plant-derived compounds, and stimulating plant defence responses. Recent reviews have reported that biochar may activate defence pathways associated with salicylic acid and jasmonate/ethylene signalling, thereby enhancing plant resistance to certain pathogens (Bhatt et al., 2024).

However, biochar should not be regarded as a universal fungicide or direct replacement for conventional disease-control measures. Its effects depend strongly on feedstock, pyrolysis conditions, application rate, soil properties, crop and pathogen. Liu *et al*. (2023) noted that biochar alone has limitations in disease suppression, particularly under field conditions, whereas its combination with microbial inoculants can strengthen and stabilize the biocontrol effect. Their review showed that biochar–microbial inoculant combinations improved disease suppression in approximately 84% of the experimental cases examined, with benefits associated with enhanced colonization of roots and rhizospheres, modification of root exudates, improvement of soil properties and activation of plant defence responses. Biochar's porous structure and moisture-retention properties can also provide physical niches that protect introduced microorganisms and improve their persistence, survival and colonization in soil and around plant roots (Ajeng *et al*., 2020; Yang *et al*., 2023).

Compost and vermicompost should not be considered forms of biochar, because they are produced through biological decomposition rather than thermal conversion. Nevertheless, they can play a complementary role in plant health management. Mature compost and vermicompost supply organic matter, nutrients and biologically active microbial communities, thereby improving soil structure, microbial activity and nutrient cycling. Their organic matrix may also provide a favourable environment or substrate for beneficial microorganisms such as *Trichoderma*, *Pseudomonas* and *Bacillus*. These microorganisms can contribute to pathogen suppression through competition for nutrients and ecological niches, antibiosis, production of hydrolytic enzymes and other metabolites, mycoparasitism and stimulation of plant defence mechanisms. Thus, compost or vermicompost combined with selected microbial inoculants may enhance rhizosphere colonization and disease-suppressive activity, although the magnitude and consistency of these effects depend on the maturity and quality of the amendment, microbial strain, soil and crop system.

An especially promising approach is therefore the development of biochar–compost/vermicompost–microbial inoculant systems. In such combinations, biochar can provide a relatively stable porous habitat and microbial carrier, while compost or vermicompost supplies readily available organic matter and nutrients that support microbial establishment and activity. Beneficial microorganisms such as *Trichoderma*, *Pseudomonas* and *Bacillus* can provide more targeted antagonistic activity against plant pathogens. Such integrated amendments could potentially improve soil health, microbial diversity, nutrient cycling, root colonization and pathogen suppression simultaneously. However, their efficacy is highly context-dependent, and field-level validation is necessary to determine suitable combinations, application rates and microbial strains for specific crops and pathogens. For Assam, the use of rice straw, crop residues, livestock manure and other locally available biomass for producing biochar, compost and vermicompost, followed by inoculation with locally adapted beneficial microorganisms, represents a particularly relevant research opportunity for sustainable Plant Health Management.

Integrated Pest and Disease Management

Integrated Pest and Disease Management represents the practical framework through which different PHM components can be combined. IPM does not reject chemical pesticides completely; instead, it prioritizes preventive and biological measures and uses pesticides only when necessary. A practical IPM programme includes:

1. Use of healthy seed and planting material.
2. Selection of resistant or tolerant varieties.
3. Crop rotation and diversification.
4. Field sanitation and removal of infected plant material.
5. Balanced nutrient and water management.
6. Regular pest and disease monitoring.
7. Conservation of natural enemies.
8. Use of microbial biocontrol agents.
9. Botanical and other low-risk interventions.
10. Need-based and judicious pesticide application.

This approach reduces unnecessary pesticide exposure while maintaining crop productivity. ICAR also emphasizes microbial biopesticides based on organisms such as *Bacillus thuringiensis*, *Trichoderma*, *Pseudomonas*, *Metarhizium* and *Beauveria* as important components of eco-friendly crop protection.

Climate-Smart Plant Health Management

Climate change introduces an additional dimension to plant health management. Temperature, rainfall, humidity and extreme weather influence both plant physiology and pest and pathogen biology. Climate-resilient plant health management therefore needs to combine adaptation, prevention and resource conservation.

Important practices include:

- climate-resilient and stress-tolerant varieties
- timely sowing based on weather information
- efficient irrigation and drainage
- alternate wetting and drying where appropriate
- rainwater harvesting and moisture conservation
- mulching
- conservation agriculture
- crop diversification
- integrated farming systems
- weather-based pest and disease advisories and
- contingency planning for floods and droughts.

These practices are particularly important in Assam because both excessive moisture and moisture deficits can occur within the same agricultural landscape. Waterlogging can favour several soil-borne and foliar diseases, whereas drought stress can weaken plants and alter pest dynamics. Climate-smart agriculture should therefore not be viewed only as a strategy for increasing yield under climate change. It should also be considered a plant-health strategy, because vigorous plants with healthy root systems and balanced nutrition are generally better equipped to withstand climatic stresses.

Crop Diversification and Ecological Pest Regulation

Monocropping can create favourable conditions for the continuous build-up of specialized pests and pathogens by providing a consistent host resource. Crop rotation and diversification can interrupt these cycles by changing host availability and modifying soil and microbial conditions. Intercropping can further suppress pest populations through host dilution, physical barriers, changes in microclimate, and enhanced activity of natural enemies. For example, mustard intercropped with cabbage and other vegetable crops can act as a trap crop for pests such as diamondback moth and aphids, attracting pests away from the main crop and facilitating targeted management. Similarly, marigold intercropping or border planting with crops such as tomato, chilli and other vegetables is commonly used as a trap or companion crop to influence pest behaviour and reduce pest pressure. Flowering plants and ecological refuges can also provide nectar, pollen and shelter for parasitoids and predators, thereby strengthening biological control and contributing to sustainable pest management. For rice-based systems in Assam, diversification with pulses, oilseeds, vegetables and other compatible crops can improve resource use and reduce dependence on a single crop. Diversification can also improve household income and resilience when one crop is affected by climatic or biological stress.

Plant Health Management through Integrated Technologies

No individual technology is likely to provide complete and consistent plant protection under all conditions. The greatest potential lies in integration. A sustainable PHM package may therefore involve: Healthy seed + resistant variety + soil testing + balanced nutrition + FYM/compost + biofertilizer + bioinoculant + crop diversification + monitoring + biological control + climate-smart water management + need-based pesticide use. For soil-borne diseases, an integrated strategy could include organic amendments, crop rotation, resistant varieties, *Trichoderma* or *Pseudomonas*, improved drainage and sanitation. For insect pests, monitoring can be combined with conservation of predators and parasitoids, pheromone or light traps where appropriate, botanical products and microbial insecticides. For example, rice pest management can combine surveillance, resistant varieties, balanced nitrogen management, conservation of natural enemies, *Trichogramma* release against suitable stem-borer situations and microbial products such as *Beauveria bassiana* where recommended.

Challenges and Limitations

Despite their potential, biological and ecological approaches face several constraints. Bioagents can have shorter shelf lives and may perform inconsistently under variable field conditions. Their efficacy depends on formulation quality, environmental conditions, compatibility with other inputs and appropriate application timing. Farmers may also face difficulties in obtaining quality microbial products, identifying genuine formulations and following recommended application procedures. Another challenge is that biological control is generally slower than chemical control and may work best as a preventive or early-stage intervention. Farmers therefore require training to understand that biological products should not necessarily be judged by the rapid knock-down effect expected from synthetic pesticides.

Biochar also requires careful selection of feedstock, production conditions and application rate. Liu *et al.* (2023) emphasized that the performance of biochar–microbial inoculant systems is influenced by the characteristics of both biochar and microbial inoculants. Finally, sustainable PHM requires stronger connections among research institutions, extension agencies, farmers, input producers and local communities. Technologies developed in laboratories must be validated under farmers' field conditions and adapted to local crops, soils and climate.

Future Perspectives and Conclusion

The future of Plant Health Management (PHM) lies in an integrated approach combining microbiology, plant pathology, soil science, agronomy, entomology, climate science and digital agriculture. Advances in microbiome research, microbial consortia and improved bioinoculant formulations can strengthen biological crop protection. Combinations of biochar, compost or vermicompost with microbial inoculants such as *Trichoderma*, *Pseudomonas* and *Bacillus* are promising because biochar can provide a stable microbial habitat, while compost and vermicompost supply organic matter, nutrients and substrates that support microbial activity and rhizosphere colonization (Liu *et al.,* 2023; Bhatt *et al*., 2024). Precision agriculture, remote sensing and weather-based disease forecasting can further enable timely and site-specific crop protection. For Assam, future research should focus on locally adapted microbial strains, agricultural-residue-based biochar, quality compost/vermicompost, natural-farming inputs, climate-resilient varieties and integrated rice-based systems, along with field validation of AAU technologies such as Biofor-Pf and *Trichoderma*-based biocontrol.

PHM shifts the focus from individual pest and pathogen control towards the health and resilience of the entire agroecosystem. Healthy soil, balanced nutrition, quality planting material, crop diversification, organic amendments, beneficial microorganisms and climate-smart practices form its foundation. Thus, sustainable PHM should not seek to replace every chemical input with a biological alternative, but should reduce unnecessary chemical dependence through prevention, ecological regulation, biological control and improved soil health, while retaining chemical pesticides as carefully managed options when required. This integrated approach can support healthier crops and soils, reduced environmental impacts and more climate-resilient agricultural livelihoods in Assam.

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Karonda Cultivation: A Profitable Opportunity for Dryland Farmers

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Karonda (Carissa carandas L.) is an underutilized indigenous fruit shrub that thrives in arid and semi-arid tracts where major fruit crops fail to perform economically. Owing to its hardy, drought-tolerant and xerophytic nature, it grows successfully on sandy, rocky, saline and wasteland soils, making it highly suitable for dryland farming systems. The plant offers multiple end uses, ranging from live hedges and bio-fences to a rich source of iron, vitamin C, pectin and several bioactive phytochemicals with medicinal value. Simple propagation methods, low input requirements, minimal pest pressure and a wide scope for value-added processing further enhance its appeal. This article compiles information on the botanical adaptability, varietal wealth, propagation, agronomic management, nutritional importance and post-harvest utilization of karonda to highlight its potential as a sustainable and remunerative crop for resource-poor dryland farmers.

Introduction

India is endowed with tremendous diversity of fruit crops ranging from temperate to tropical regions, and among these, several underutilized and minor fruit crops occupy an important place (Singh et al., 2025a). Such minor fruits are often described as protective foods because, besides being hardy, they reduce the risk of over-dependence on major fruit crops and help preserve dietary diversity (Singh et al., 2025a). Karonda (Carissa carandas L.) is one such crop that has gained recognition for its nutritional advantages, therapeutic qualities and potential for diversified applications (Singh et al., 2025a). It is a hardy, evergreen, spiny and indigenous shrub that is widely grown across India and is popularly known by names such as Bengal currant, carandas plum, karonda, karanda and Christ's Thorn (Banik et al., 2012). Because it is very hardy and drought tolerant, karonda thrives well throughout tropical and subtropical climates, including the dry tracts of Bihar, West Bengal, Uttar Pradesh and South India (Banik et al., 2012). It is also a drought-resistant plant that can be grown in a wide range of soil types, which further explains its long-standing association with arid zone horticulture (Singh et al., 2020).

Botanical Description and Climatic Adaptability

Morphologically, karonda exhibits a dense, spinous branching habit with a characteristic Y-shaped branch structure, and its leaves are opposite, glossy green on the upper surface and oblong to ovate in shape (Singh et al., 2025a). The plant produces fragrant white flowers in small terminal clusters, primarily blooming from March to April, with fruit maturation occurring from August to September (Singh et al., 2025a). Taxonomically, karonda belongs to the genus Carissa, a member of the Apocynaceae family with a chromosome number of 2n=22, and the genus comprises about 30 species native to Malaysia, tropical Asia, Australia and South Africa, of which five species are native to India (Singh et al., 2025a). Carissa carandas is described as an evergreen thorny shrub of the Apocynaceae family whose small berry-shaped fruits are used as an additive in pickles or as a spice, particularly in northern India (Singh et al., 2020). In terms of climatic and soil adaptability, karonda is a xerophytic plant that is well adapted to arid and semi-arid climates and can be grown on sandy, rocky and otherwise poor soils typical of dry regions, although growth and yield are higher on deep loamy or alluvial soils (Singh et al., 2025a). It can also tolerate sodic and saline soils with a pH of

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up to 8.5, which makes it especially suited to marginal and wasteland sites that are unsuitable for other commercially important crops (Singh et al., 2025a; Banik et al., 2012).


Genetic Diversity and Improved Varieties

Genetic diversity plays a crucial role in the adaptability, resilience and improvement potential of karonda, and as an underutilized hardy fruit crop, it exhibits considerable variability in traits such as fruit size, colour, taste, growth habit and tolerance to biotic and abiotic stresses (Singh et al., 2025a). Karonda populations show variation in fruit colour ranging from green to white, pink, red and deep purple or brown at maturity, and fruit size, shape and taste also vary among genotypes (Singh et al., 2025a). Studies employing molecular markers such as RAPD, ISSR and SRAP have helped assess this genetic diversity and population structure, thereby assisting in the identification and selection of superior genotypes for conservation and breeding (Singh et al., 2025a). A survey conducted in eastern Uttar Pradesh identified four types of karonda fruits, namely green, white with pink blush, green with purple blush and maroon, and these are generally classified into two broad categories, pickling type and table purpose (Singh et al., 2025a). Selection-based improvement work carried out at various institutes has resulted in released cultivars such as Pant Manohar, Pant Suvarna and Pant Sudarshan, which are pickle-type genotypes with recorded yields of about 22 to 29 kilograms per plant, as well as table-purpose selections such as Konkan Bold and CHES K-II-7, and arid-zone varieties such as Maru Gaurav and Thar Kamal that record yields of around 40 and 13 kilograms per tree respectively (Singh et al., 2025a). Such collection, conservation and evaluation of germplasm, along with standardization of vegetative propagation techniques, is being carried out successfully in different parts of India (Banik et al., 2012).

Propagation Techniques Suited to Dryland Establishment

Karonda is generally propagated through seeds, although asexual methods such as stem cutting, air layering, stooling, budding and grafting can also be used, while mass-scale production of clonal planting material can be achieved through micropropagation (Singh et al., 2025a). Seeds are extracted from fully ripened fruits during August and September and sown immediately because they are recalcitrant in nature, and the highest germination rate of 63.32 per cent was recorded with fresh seeds, although seeds stored for up to 12 days under ambient conditions also maintained good germination and vigour (Singh et al., 2025a). Soaking seeds in cow dung slurry for 24 hours produced the highest germination of 62.67 per cent with high vigour indices, whereas soaking seeds in IBA at 20 ppm for 12 hours gave an even higher germination percentage of 80.83 per cent (Singh et al., 2025a). Among vegetative methods, cuttings about 25 centimetres long with four to five nodes, planted during the monsoon season in a sand, soil and farmyard manure medium in a 1:2:1 ratio and treated with IBA at 8000 ppm, recorded the highest rooting percentage of 39.43 per cent, while softwood grafting using a two-month-old scion covered with a polyethylene sheet resulted in a graft survival rate of 97.31 per cent, and air layering with 5000 ppm IBA induced rooting most effectively with 90 per cent survival (Singh et al., 2025a). Because conventional propagation methods such as seeds, cuttings, grafting, air layering and stooling have given variable and often unsatisfactory results, and because a large number of plants are required per unit area for hedge plantations, an alternative method for rapid and large-scale multiplication has been considered necessary to expand the area under this underutilized crop (Rai &

Misra, 2005). In response, a micropropagation protocol was developed in which shoot tips collected from field-grown mature plants of the cultivar Pant Sudarshan were cultured on Murashige and Skoog basal medium supplemented with benzyladenine and indole-butyric acid during different seasons, and the maximum sprouting rate was obtained using 1.5-centimetre-long explants collected during the spring season of February to March, followed by those collected during the summer season of April to June (Rai & Misra, 2005). Shoot proliferation was found to be highest on MS basal medium supplemented with 3.0 mg per litre BA, while rooting of the resulting microshoots was best in half-strength MS medium with 0.8 mg per litre IBA and 0.2 mg per litre naphthalene acetic acid, after which the rooted plantlets were successfully acclimatized in a potting mixture of vermiculite, sand and soil in a 1:1:1 ratio (Rai & Misra, 2005). Such tissue-culture-based multiplication approaches are also highlighted as important tools for overcoming the planting-material constraints that limit the commercial expansion of underutilized dryland fruit crops in general (Singh et al., 2025b).

Agronomic Management for Dryland Orchards

Karonda is generally planted as a live fence, although it is also suitable for both block and hedgerow planting, with the monsoon season of July to August considered ideal for planting, while planting during the spring season of February to March is also possible where assured irrigation is available (Singh et al., 2025a). Under a square planting system, plants may be spaced 3 metres apart, reduced to about 2 metres under high-density planting, or widened to 4 to 5 metres to facilitate intercultural operations and intercropping, while for hedge planting a spacing of 60 centimetres in double rows along orchard boundaries is recommended (Singh et al., 2025a). With regard to nutrition, plants used for protective hedges require minimal fertilization, although applying farmyard manure or compost is beneficial since plants gradually become depleted after bearing two crops and show signs of dieback, and applying 10 to 15 kilograms of well-rotten farmyard manure or compost per plant before the flowering stage is therefore considered useful (Singh et al., 2025a; Banik et al., 2012). For optimal growth and productivity, leaf nitrogen levels between 0.99 and 1.37 per cent are recommended, while applying a 1.0 per cent urea solution during fruit set, followed by 0.50 per cent mono-potassium phosphate 20 days after fruit setting, led to higher fruit retention of 95.20 per cent, a pre-rainfall fruit yield gain of 64 per cent and superior fruit quality characterized by the highest total soluble solids (Singh et al., 2025a). Regarding plant protection, karonda typically shows little susceptibility to pests or diseases in arid regions, although leaf-eating caterpillars and fruit flies have been reported in certain locations, making orchard sanitation an important management practice (Singh et al., 2025a). Among plant bio-regulators, gibberellic acid at 1000 ppm was found most effective for enhancing initial plant growth, while application of 20 ppm NAA at 50 per cent flowering and again 21 days after the first spray led to the highest fruit set of 93 per cent, fruit retention of 83 per cent and fruit yield of 4 kilograms per plant under the alluvial zone of West Bengal, whereas gibberellic acid at 20 ppm proved effective for improving total soluble solids, total sugars, ascorbic acid and anthocyanin content of the fruit (Singh et al., 2025a). For training and canopy management, karonda may be trained on single or double stems by removing lateral shoots up to 15 to 20 centimetres from ground level to form the main stem, with only mild pruning required each year during November and December, since floral buds develop on new season growth and old branches seldom flower (Singh et al., 2025a). Owing to its xerophytic nature, karonda needs very little irrigation, requiring watering every 10 to 15 days in winter and every 6 to 7 days in summer through the basin or flood method, while drip irrigation and deficit irrigation at the rate of 0.5 to 0.8 of pan evaporation have been suggested for efficient water use in arid and semi-arid zones (Singh et al., 2025a). Mulching is also recommended, with organic materials such as dry leaves, straw, sugarcane trash and compost improving infiltration and water-holding capacity, while black plastic mulch combined with 15 litres of irrigation water at 15-day intervals has been reported to enhance fruit quality attributes (Singh et al., 2025a). During the early years of orchard establishment, the inter-row space can be effectively utilized for growing vegetables and leguminous intercrops that provide additional income, and multi-storeyed cropping systems such as aonla-guava-karonda and aonla-ber-karonda have been suggested for salt-affected soils (Singh et al., 2025a). Under favourable management, karonda plants begin bearing fruit two to three years after planting, and reported yields vary considerably with variety and growing environment, ranging from about 22 to 29 kilograms per tree per year under tarai conditions to as high as 30.87 kilograms per tree under Maharashtra conditions and 15 to 22 kilograms per tree under South Indian conditions (Singh et al., 2025a).

Nutritional Composition and Medicinal Significance

Karonda holds considerable importance because of its nutritional composition, medicinal properties and varied uses, and it is recognized as a source of phytochemicals with potential health benefits, including anti-inflammatory and anti-cancerous properties (Singh et al., 2025a). The fruit has been described as one of the richest sources of iron, vitamin C and pectin among indigenous fruits (Singh et al., 2020). Phytochemical analysis has shown that the plant contains a wide variety of flavonoids, phenolic acids, steroids, volatile oils, lignans, alkaloids and polysaccharides, and these compounds exhibit a range of pharmacological activities including antioxidant, anti-inflammatory, antidiabetic, antimicrobial and antifungal properties (Singh et al., 2020). In traditional medicine, the roots of karonda have been reported to possess bitter, stomachic, antidiarrheal and antianthelmintic qualities, with root extracts used for chest pain and leaf extracts used for fever and applied externally for skin ailments such as leprosy (Singh et al., 2025a). The fruits themselves are used in traditional herbal medicine to address conditions such as anorexia, anaemia, ulcers, fresh and infected wounds, skin problems, urinary issues and diabetic ulcers, and they are also valued for their aphrodisiac, antipyretic, appetizer, anthelmintic and astringent properties (Singh et al., 2025a). Ripe fruits in particular are described as sweet, cooling and appetizing, and are considered useful in controlling burning sensation, skin diseases, scabies and pruritus (Singh et al., 2025a).

Post-Harvest Handling and Value-Added Processing

Harvesting of karonda often requires three to four picking cycles since not all fruits mature at the same time, and a complete harvest from a single plant typically needs four to six pickings, with a change in fruit colour together with a specific gravity exceeding 1.0 serving as an effective indicator of ripeness (Singh et al., 2025a). After harvesting, unripe fruit can be stored at room temperature for five to seven days, whereas fully ripe fruit can be stored for only about two days, which makes timely processing important (Singh et al., 2025a). The astringent and sour unripe fruits are used to prepare chutneys and pickles that are highly sought after in the global market, while the mature fruits are consumed as dessert and processed into sauce, syrup, squash, jam and jelly, and dried fruits are sometimes used as a substitute for raisins (Singh et al., 2025a). Karonda fruits have also been utilized in processed products such as jam, jelly, squash, syrup and chutney that are in great demand in the international market, reflecting the strong commercial potential of value addition (Banik et al., 2012). Like cherries, the fruits can be candied and are known as Nakal cherry in some areas, and the white latex present in unripe fruits is additionally utilized in the production of chewing gum and rubber (Singh et al., 2025a). With

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respect to drying and storage technologies, low-power microwave drying and sun drying have been reported as the most effective processing methods for retaining nutritional compounds such as total phenols, flavonoids, anthocyanins, vitamin C, antioxidant activity and minerals in karonda powder, while osmotic pre-treatment with sodium chloride solution for three hours produced the maximum sensory score after extended storage, and osmo-dried karonda prepared using 70 degree Brix sugar syrup showed improved colour, texture, taste and acceptability and could be stored for more than 90 days (Singh et al., 2025a). Karonda juice can also be blended with other fruit juices such as guava, papaya and pineapple in different proportions, and the combination of karonda juice with pineapple juice was found to offer the best organoleptic quality and acceptability (Singh et al., 2025a).

Conclusion

Karonda represents a hardy, low-input and multipurpose fruit crop that is exceptionally well suited to the constraints of dryland farming. Its ability to establish on marginal, sandy, saline and wasteland soils, combined with minimal irrigation and fertilizer requirements, makes it economically attractive for resource-poor farmers operating under arid and semi-arid conditions. Availability of improved varieties, simple propagation routes including seed, vegetative and tissue-culture methods, and a wide range of value-added products such as jams, jellies, squashes, pickles, candied fruit and juice blends further strengthen its commercial appeal. Given the growing consumer interest in nutrient-dense and medicinally important foods, expanding karonda cultivation in wastelands and arid regions, alongside improved post-harvest handling and marketing infrastructure, can convert this currently underutilized shrub into a dependable source of additional income for dryland farming communities.

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Role of Different Seed Coating Technologies in Modulating Early Root Development and Germination Physiology of Lentil

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Legume root systems have been less intensively studied than the roots of cereal (Gregory 1988). The emerging root radicle of legumes forms a taproot, which subsequently allows lateral root development. Rapid root and canopy development and growth facilitates successful establishment of seedlings. Vigorous root development is important for seedling survival under conditions under which the soil surface dries rapidly whilst sufficient soil moisture remains available in deeper zones. Furthermore, the type of root distribution required for a crop species depends on the target environment. With regard to food legumes, little information is available on seedling shoot and root systems in lentil (*Lens culinaris Medikus*) (Mia *et al.,* 1996). The root is the prime organ involved in water uptake. The contribution of root traits becomes more critical in water-limited environments, extracting water from deeper layers. The above-ground traits have always gained the attention of breeders, while the root traits have often been neglected due to their complex phenotyping and low heritability (Malamy *et al.,* 2005).

Although root traits play a decisive role in seedling establishment and stress tolerance in lentil, their improvement through conventional breeding has been slow because of the difficulty in phenotyping root systems and their complex genetic control. This limitation highlights the need for complementary, non-genetic approaches that can enhance early root growth and seedling vigor without altering the plant's genome. One such promising approach is seed-based interventions, particularly seed coating technologies, which act directly at the earliest stage of plant development. By modifying the seed microenvironment and delivering beneficial compounds at the point of germination, seed coating offers a practical strategy to stimulate root growth, improve early establishment, and ultimately support better root system development under both optimal and stress conditions.

Seed coating is the recent improvement which can alter seed mechanism in improved way. Seed coating is a process of applying exogenous materials to the surface of the natural seed coat (Kaufman *et al.,*1991). Coatings decrease the risk of imbibitional damage during germination, as imbibition can be regulated to provide increased or decreased moisture in line with the optimal amount required for germination (Avelar *et al.,* 2012). This practice is used to modify the physical properties of seed and make easy delivery of active ingredients. The physical modification of seed aims to improve seed handling through standardization of seed weight and size and in some cases, where the aim is to reduce friction and improve flowability. (Halmer *et al.,* 2008).

Seed coating operates through multiple mechanisms, including the controlled release of nutrients, enhanced water retention, and improved microbial interactions and benefits are shown in Fig:1. The choice of coating materials significantly influences seed performance (Davis., 2016).

Coating Materials : Polymers Enhance adhesion and controlled release of bioactive agents, ensuring that seeds receive nutrients and protective substances in a targeted manner. Water retentive polymers help sustain moisture levels in the seed microenvironment, promoting early germination and strong root development.

Biological Agents: Improve seedling establishment and protect against soil-borne diseases, boosting early-stage plant immunity and resilience. Beneficial bacteria and fungi incorporated into coatings help in nitrogen fixation and phosphorus solubilizing, supporting plant nutrition and reducing dependence on synthetic fertilizers.

Nutrients: Provide essential macro and micronutrients for early growth, improving root and shoot development for better crop yields. Micronutrient-enriched coatings, such as zinc and boron applications, have been demonstrated to enhance plant vigour and disease resistance (Dhaliwal *et al.,* 2022).

Adhesive Agents : Binders such as gum Arabic and cellulose-based polymers ensure uniform coating adherence, improving seed stability and reducing material loss. These adhesives play a crucial role in preventing coating fragmentation and ensuring the longevity of the applied treatment, particularly during seed storage and transportation. Adhesive selection is essential in determining the release rate of nutrients and active compounds, optimizing plant uptake efficiency.

Lentil seeds are highly sensitive during germination due to their small size and thin seed coat, which make them prone to rapid and uncontrolled water uptake (imbibitional injury), mechanical damage from soil crusting, and stress caused by fluctuating soil temperatures. These vulnerabilities often result in delayed emergence, poor stand establishment, and uneven seedlings. The technologies that can regulate water entry, protect the seed surface, and buffer environmental stresses are critically important. Some of them are as follows:

Polymer film coatings (thin layer coatings)

Films coatings are made out of edible biopolymers and additives that are safe for consumption (Farshi *et al.,* 2023). Different biological components, including polysaccharides, proteins, and lipids, can be employed in films coatings, either alone or in combination (Al-Sahlany., 2017). Each material on its own can create film coatings with unique properties. However, combining materials and incorporating plasticizers and surfactants is commonly employed to improve their ultimate characteristics, including flexibility, barrier properties, and optical qualities (Guimaraes *et al.,* 2018). Proteins and polysaccharides tend to create stiff and brittle films. Therefore, plasticizers are often required in conjunction with these polymers to produce flexible and easier-to-handle edible films. Plasticizers have low molecular weight, and they can reduce the distance between polymer molecules, decreasing the ratio of crystalline to amorphous regions in protein- and polysaccharide-based edible films (Farshi *et al.,* 2023). Hydrophilic and semi-permeable polymers form a uniform protective film around lentil seeds. This coating moderates the rate of water absorption, reducing imbibitional shock, while still allowing oxygen diffusion. In lentil, this helps prevent seed coat cracking and improves germination uniformity under variable moisture conditions.While thin polymer film coatings mainly function by regulating imbibition and gas exchange at the seed surface, additional physical protection and improvements in seed handling can be achieved through thicker coating approaches such as encrusting and pelleting.

Encrusting and pelleting coatings

Encrustation is a pioneering method of seed enhancement that includes applying a thick coating all around the seed, significantly adding buildup to increase weight and volume while maintaining its natural shape (Pedrini *et al.,* 2017 and Ahsan *et al.,* 2022). Encrusting is a hybrid of film coating and pelleting which aims at physical modification of seed to improve handling and palatability through standardization of seed weight and size. (Taylor *et al.,* 1998, Halmer., 2008 and Avelar *et al.,* 2012). This

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provides seeds a fine surface treatment with a blend of ingredients to create an inert organic and, as well as insecticides, colours and adhesives. Encrusting with botanicals are cheap and non-toxic and provide protection from pests and diseases during germination and early crop growth (Kumar *et al.,* 2015). Botanical seed treatments are derived from naturally available sources that has synergistic influence on early and uniform seed emergence as well as increased resistance to pests and diseases in the early stages of crop development. In lentil, these coatings help overcome problems of poor soil contact and soil crusting by improving seed–soil interface, enabling more uniform moisture availability and stronger seedling emergence.

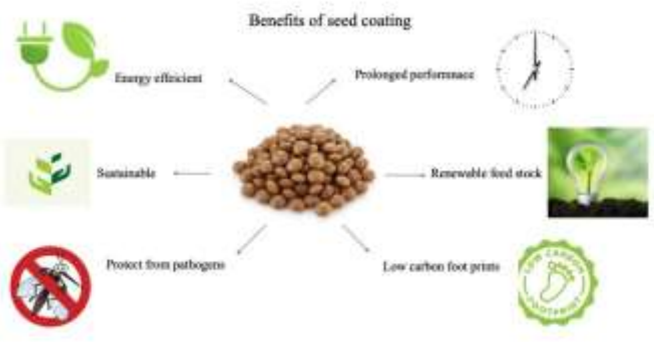

Fig:1 Benefits of seed coating

Bioactive and nutrient-loaded coatings

Beyond physical modification and protection, enabling the targeted delivery of nutrients, beneficial microorganisms, and stress-mitigating compounds to the sensitive lentil seed. Nano-fertilisers offer an emerging new frontier, providing controlled release, increased solubility, and higher absorption efficiency than conventional fertilisers. Their use has been proven to increase productivity, improve nutrient synchrony with crop needs, and reduce leaching and volatilization (Gopinath *et al.,* 2025). Similarly, microbial inoculants and bio-fertilisers, including rhizobia, P-solubilizing bacteria, and arbuscular mycorrhizal fungi, are increasingly deployed as microbial consortia that enhance nutrient cycling, root growth, and stress resilience. Customized fertiliser blends and integrated nutrient management (INM) strategies are also becoming popular. Blends suited to soil deficiencies and crop requirements, enhanced with secondaryand micro- nutrients, have improved yields and quality in many pulse and oilseed systems (Kumar *et al.,* 2025). Coatings containing micronutrients, antioxidants (such as ascorbic acid), polymers (PEG, cellulose derivatives), or beneficial microbes create a protective microenvironment around sensitive lentil seeds. These systems buffer temperature and moisture stress, reduce oxidative damage during early imbibition, and supply readily available nutrients, enhancing early vigor.

Adhesive-based binder systems (gum Arabic, cellulose polymers);

Gum-based films and coatings could provide several benefits, such as extended shelf life, biocompatibility and being environmentally friendly, good mass transfer barrier characteristics, carriers of foods additives such as antioxidants, vitamins, and antimicrobial compounds (Dangi *et al.,* 2023).Adhesives ensure strong adherence of polymers and actives on the delicate lentil seed surface. This prevents coating breakage during handling and ensures gradual release of nutrients and protectants during storage and after sowing, which is critical for sensitive seeds like lentil.

Challenges in Developing Formulation for Seed Coating

Numerous studies are conducted on SC with totally different materials like polymer, carriers, fungicides, insecticide etc. however the studies remained confined to the laboratories solely. Till date, there's no formulation for SC with biological alone or in combinations with different seed coating materials, are accessible on the commercial scale. The foremost limiting step in commercializing the formulation for SC is shelflife. Apart from shelf life, compatibility of biological with polymers and different ingredients of coating assurance of correct loading of precise number of cells on seed and stability are different vital characters if coatings ought to be applied as multilayer (Harman., 1991). All these studies are still in experimental field as a result of most of the formulations developed are tested below artificial and controlled conditions and so established inadequate for field conditions (Prasad., 2013). Microbes conjointly need aeration to survive and stay alive until the coated reaches the soil. Thus, porosity of the polymer is additionally a vital factor in survivability of microbes and effectiveness of the coating.

A perfect coating ought to have following characteristics;

a. Fungicide ought to be compatible with microbes

b. Polymer ought to have hygroscopic and moisture retention properties

c. Coating ought to be skinny, water soluble and may not hamper the normal germination of seed.

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Chandipura Virus: A Monsoon-Linked Threat to Children in India

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Introduction

Chandipura virus (CHPV) is a rare but highly lethal vector-borne pathogen that causes acute encephalitis syndrome (AES), predominantly affecting children under 15 years in India (Lodha et al., 2025; Mourya et al., 2025; Sharma et al., 2026). First identified in 1965 in Chandipura village, Maharashtra, the virus resurfaces periodically—especially during monsoon seasons—when sandfly populations surge (Lodha et al., 2025; Mourya et al., 2025; Sharma et al., 2026). With case-fatality ratios historically ranging from 56% to 75% and no specific antiviral or vaccine available, early recognition and intensive supportive care remain critical to survival (Mourya et al., 2025; Sharma et al., 2026; Yadav et al., 2024). Despite seven decades of evidence, CHPV remains a neglected public health challenge, with recurring outbreaks exposing gaps in surveillance, diagnostics, and vector control in rural and tribal India (Sharma et al., 2026; Yadav et al., 2024).

Historical Background and Virology

CHPV was first isolated in 1965 from patients presenting with a dengue-like febrile illness in Chandipura, a village in Nagpur district, Maharashtra (Lodha et al., 2025; Mourya et al., 2025). It is a bullet-shaped, enveloped virus with a single-stranded, negative-sense RNA genome, classified under the family *Rhabdoviridae*, genus *Vesiculovirus* (Lodha et al., 2025; Sapkal et al., 2018). The virus is antigenically and genetically distinct from other vesiculoviruses such as rabies and vesicular stomatitis virus, though it shares structural similarities (Lodha et al., 2025; Sapkal et al., 2018).

Genomic analyses indicate that CHPV is relatively stable over time, with limited antigenic drift observed across isolates from different outbreaks (Sharma et al., 2026; Yadav et al., 2024). This stability is encouraging for vaccine development but also suggests that the virus has maintained its virulence and neurotropism over decades (Sharma et al., 2026).

Epidemiology and Geographic Distribution

CHPV infections have been documented primarily in central, western, and southern India, with outbreaks reported in Maharashtra, Gujarat, Andhra Pradesh (now Telangana), Madhya Pradesh, Karnataka, and Rajasthan (Mourya et al., 2025; Sharma et al., 2026; Yadav et al., 2024). The 2024 outbreak was the largest in two decades, with 245 AES cases and 82 deaths reported across India; 64 were CHPV-confirmed, mostly in Gujarat (Sharma et al., 2026; Yadav et al., 2024; World Health Organization, 2024).

The virus exhibits a distinct seasonal pattern, with cases peaking during and shortly after the monsoon (June–October), coinciding with increased sandfly breeding and activity (Mourya et al., 2025; Sharma et al., 2026). Outbreaks are concentrated in rural and tribal areas characterized by poor housing (mud walls, cow-dung plaster), inadequate sanitation, and proximity to livestock and stagnant water—ecological niches that favor sandfly proliferation (Mourya et al., 2025; Sharma et al., 2026).

Seroprevalence studies suggest that exposure to CHPV is widespread in endemic regions, but clinical disease is rare and almost exclusively affects children under 15 years, likely due to the absence of prior immunity (Mourya et al., 2025; Sharma et al., 2026). Adults in endemic areas often show IgG antibodies without a history of severe illness, indicating subclinical or mild infections that confer lasting immunity (Mourya et al., 2025).

Transmission Dynamics and Vector Ecology

CHPV is primarily transmitted through the bite of infected female sandflies, particularly species of the genera *Phlebotomus* and *Sergentomyia* (Sharma et al., 2026; Tesh & Modi, 1993). The virus has been isolated from *Phlebotomus papatasi*, *P. stantoni*, and *Sergentomyia (Grassomyia) indica*, among others (Sharma et al., 2026; Tesh & Modi, 1993). Experimental studies have demonstrated transovarial transmission of CHPV in *P. papatasi*, suggesting that the virus can persist in sandfly populations across generations even in the absence of vertebrate hosts (Tesh & Modi, 1993).

Mosquitoes and ticks have also been implicated as potential secondary vectors, though their role remains less defined (Lodha et al., 2025; Mourya et al., 2025). No evidence of human-to-human transmission has been documented, and there is no known animal reservoir, although serological evidence of infection has been found in cattle, goats, and other domestic animals in endemic areas (Mourya et al., 2025; Sharma et al., 2026).

The One Health framework—integrating human, animal, and environmental health—is increasingly emphasized for CHPV control, given the complex interplay between vector ecology, housing conditions, livestock presence, and climate (Mourya et al., 2025; Sharma et al., 2026).

Pathogenesis and Clinical Features

CHPV is a neurotropic virus, meaning it has a strong affinity for nervous tissue. After inoculation via a sandfly bite, the virus replicates locally and then disseminates via the bloodstream (viremia) to the central nervous system (Sharma et al., 2026; Lodha et al., 2025). The virus breaches the blood-brain barrier through cytokine-mediated increased permeability and induces neuronal apoptosis via Fas- and NF-κB-linked pathways, leading to acute encephalitis (Sharma et al., 2026).

The incubation period is short, typically 2–5 days (Lodha et al., 2025). Illness begins abruptly with high-grade fever, severe headache, myalgia, vomiting, and sometimes diarrhea (Lodha et al., 2025; Mourya et al., 2025). Within 24–72 hours, neurological symptoms emerge: altered sensorium, confusion, seizures (often generalized tonic-clonic), focal deficits, and rapid progression to coma (Lodha et al., 2025; Sharma et al., 2026; Yadav et al., 2024).

Case-fatality ratios in outbreaks have ranged from 56% to 75%, with death often occurring within 48 hours of symptom onset in fulminant cases (Lodha et al., 2025; Mourya et al., 2025; Sharma et al., 2026). Survivors may experience long-term neurological sequelae, including cognitive impairment, motor deficits, and epilepsy, though systematic follow-up data are limited (Sharma et al., 2026).

Diagnosis

Early diagnosis is challenging because initial symptoms mimic common viral fevers and other arboviral infections such as dengue, chikungunya, and Japanese encephalitis (Lodha et al., 2025; Mourya et al., 2025). Definitive diagnosis relies on laboratory confirmation:

- **Serology**: Detection of CHPV-specific IgM antibodies in serum or cerebrospinal fluid (CSF) using enzyme-linked immunosorbent assay (ELISA) (Lodha et al., 2025; Sharma et al., 2026).
- **Molecular methods**: Reverse transcription polymerase chain reaction (RT-PCR) targeting the viral nucleoprotein or glycoprotein genes in blood or CSF (Lodha et al., 2025; Sharma et al., 2026; Yadav et al., 2024).
- **Virus isolation**: Inoculation of clinical samples into suckling mice or cell cultures,

though this is rarely performed outside reference laboratories (Lodha et al., 2025).

Imaging (CT/MRI) may show nonspecific findings such as cerebral edema or basal ganglia involvement but is not diagnostic (Lodha et al., 2025). Lumbar puncture typically reveals lymphocytic pleocytosis and elevated protein in CSF (Lodha et al., 2025).

Access to RT-PCR and IgM ELISA is limited to reference centers such as the National Institute of Virology (Pune), Manipal Institute of Virology, and select state laboratories, contributing to underdiagnosis and delayed outbreak response (Sharma et al., 2026; Yadav et al., 2024).

Treatment and Management

There is no specific antiviral therapy or licensed vaccine for CHPV as of 2026 (Lodha et al., 2025; Mourya et al., 2025; Sharma et al., 2026). Management is entirely supportive and must be initiated early in a facility capable of intensive care:

- **Airway and breathing**: Endotracheal intubation and mechanical ventilation for patients with coma or respiratory failure (Lodha et al., 2025; Yadav et al., 2024).
- **Seizure control**: Benzodiazepines (e.g., lorazepam, midazolam) followed by antiepileptics (e.g., phenytoin, levetiracetam) (Lodha et al., 2025).
- **Intracranial pressure management**: Head elevation, mannitol or hypertonic saline, and careful fluid balance (Lodha et al., 2025).
- **Hemodynamic support**: Vasopressors for shock, correction of electrolyte imbalances, and management of secondary infections (Lodha et al., 2025; Yadav et al., 2024).

Experimental antivirals such as favipiravir and ribavirin have shown in vitro activity against rhabdoviruses but have not been evaluated in human CHPV infections (Sharma et al., 2026). Recombinant glycoprotein-based vaccine candidates have demonstrated immunogenicity in animal models but remain in preclinical stages (Sharma et al., 2026).

Prevention and Public Health Response

In the absence of vaccines or specific therapeutics, prevention hinges on reducing vector-human contact and improving environmental conditions (Mourya et al., 2025; Sharma et al., 2026; Yadav et al., 2024). Key interventions include:

- **Personal protection**: Use of insecticide-treated nets (ITNs), long-sleeved clothing, and child-safe repellents, especially during evening and night hours when sandflies are most active (Mourya et al., 2025; Sharma et al., 2026).
- **Vector control**: Indoor residual spraying (IRS) with pyrethroids, larviciding of stagnant water, and environmental management to eliminate sandfly breeding sites (cracks in walls, animal sheds, organic waste) (Mourya et al., 2025; Sharma et al., 2026).
- **Housing improvement**: Replacement of mud walls and cow-dung plaster with cement, installation of wire-mesh windows, and improved ventilation reduce indoor sandfly densities (Mourya et al., 2025).
- **Surveillance and early warning**: Integration of CHPV testing into India's Integrated Disease Surveillance Programme (IDSP) and AES investigation protocols, with rapid sample transport to reference labs (Sharma et al., 2026; Yadav et al., 2024).
- **Community engagement**: Health education campaigns during monsoon months to promote net use, early care-seeking, and environmental sanitation (Mourya et al., 2025; Sharma et al., 2026).

The 2024 and 2026 outbreaks prompted multi-sectoral responses involving the Ministry of Health, state health departments, the National Centre for Disease Control (NCDC), and vector-control agencies, with deployment of rapid response teams and enhanced surveillance in affected districts (World Health Organization, 2024; Yadav et al., 2024).

Research Gaps and Future Directions

Despite seven decades of recognition, critical knowledge gaps persist (Sharma et al., 2026; Mourya et al., 2025):

- **Definitive vector species**: While *Phlebotomus* and *Sergentomyia* sandflies are strongly implicated, the primary vector(s) responsible for human transmission remain unconfirmed in many endemic regions (Sharma et al., 2026; Tesh & Modi, 1993).
- **Animal reservoirs**: Serological evidence suggests infection in domestic animals, but their role in the transmission cycle is unclear (Mourya et al., 2025; Sharma et al., 2026).
- **Long-term outcomes**: Systematic follow-up of survivors to document neurological, cognitive, and developmental sequelae is lacking (Sharma et al., 2026).
- **Vaccine and antiviral development**: No candidate has progressed to human trials, despite promising preclinical data (Sharma et al., 2026).
- **Point-of-care diagnostics**: Rapid, field-deployable tests for CHPV are urgently needed to enable early detection and outbreak containment (Sharma et al., 2026; Yadav et al., 2024).

A coordinated One Health approach—linking human health surveillance with entomological monitoring, animal serosurveys, and environmental risk mapping—is essential to mitigate the recurring burden of this neglected childhood neurotropic arbovirus (Mourya et al., 2025; Sharma et al., 2026).

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The Invisible Farmers: How Soil Microbes Feed Our Crops

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Soil is more than a physical medium for crop production; it is a living ecosystem in which microorganisms influence plant nutrition, growth and resilience. Bacteria, fungi and other microbes decompose organic residues, transform nutrients, stimulate roots and interact with plants in the rhizosphere. Recent experimental studies demonstrate that microbial inoculants can modify soil microbial communities and nutrient transformations, while microbial bio stimulants can improve crop growth and yield. In groundnut, combined application of beneficial rhizobacteria enhanced growth, photosynthetic pigments, nodulation and yield under pot and field conditions. Studies with arbuscular mycorrhizal fungi and plant-growth-promoting bacteria further show that microbial partners can act synergistically to reshape root development and rhizosphere communities. Emerging research also indicates that crop varieties differ in their ability to interact with microbiomes. Understanding these invisible farmers can therefore support efficient nutrient management, climate resilience and sustainable agriculture. Future farming may focus on managing beneficial microbial communities alongside crops.

1.Introduction

When we look at a healthy agricultural field, we usually notice the crop above the soil the green leaves, vigorous stems, flowers, pods and grains. We rarely think about the enormous biological activity taking place beneath our feet. Hidden within every gram of fertile soil are diverse communities of microorganisms that continuously interact with plant roots and participate in processes essential for crop production.

These microorganisms include bacteria, fungi, archaea and other microscopic organisms. They decompose crop residues, recycle nutrients, transform organic and inorganic compounds, influence soil structure and interact directly with plants. Some microorganisms can fix atmospheric nitrogen, while others help mobilize phosphorus, potassium, iron and other nutrients. Some produce compounds that influence root development, while others can contribute to plant protection and stress tolerance.

For this reason, microorganisms can be described as the **"invisible farmers" beneath our crops**.

The importance of these invisible workers is increasingly being revealed through modern agricultural microbiology. Earlier research often focused on individual microorganisms and their specific functions. Today, researchers are increasingly studying entire microbial communities the soil microbiome and investigating how microorganisms interact with plants, soil and each other.

Recent research provides strong evidence that manipulating these microbial communities can influence nutrient availability and crop performance. Li et al. (2023), for example, used metagenomic approaches to investigate how a bacterial biofertilizer altered soil microbial communities and nutrient transformations. Their study found increases of 46.7% in fast-acting nitrogen and 88.6% in fast-acting phosphorus following application of the bacterial agent, highlighting the connection between microbial activity, nutrient availability and plant growth.

Thus, soil should not be regarded simply as a place where roots grow. It should be viewed as a *living biological system.*

2. The Soil: A Living Ecosystem

A handful of soil may appear lifeless, but microscopically it is a highly active ecosystem. Microorganisms continuously compete, cooperate, communicate and exchange metabolites. Some microorganisms obtain energy from organic matter, while others interact closely with plant roots. The region immediately surrounding plant roots is known as the rhizosphere. It is one of the most biologically active zones in soil because roots release a variety of compounds into their surroundings.

These compounds include sugars, amino acids, organic acids and other metabolites collectively known as root exudates. They provide nutrients and chemical signals that influence microorganisms living around the roots. Consequently, the plant itself helps shape its microbial environment. The relationship can be thought of as a biological marketplace. Plants provide carbon compounds to microorganisms, while beneficial microorganisms can provide services to plants, including nutrient mobilization, growth stimulation and protection from environmental stresses.

This relationship is not random. The plant species, genotype, root characteristics, soil conditions and agricultural practices can all influence which microorganisms become established around the roots. The concept of the plant–microbiome partnership has therefore become increasingly important in modern agricultural science.

3. Microbes as Nature's Nutrient Managers

One of the most important contributions of soil microorganisms is their role in nutrient cycling.

Nitrogen: From Atmosphere to Plant

Nitrogen is essential for plant growth because it is required for amino acids, proteins, nucleic acids, chlorophyll and many other cellular components.

Although the atmosphere contains a large quantity of nitrogen gas, plants cannot directly utilize atmospheric N_2. Certain microorganisms possess nitrogenase enzymes that enable them to convert atmospheric nitrogen into biologically useful forms through biological nitrogen fixation.

Other soil microorganisms participate in nitrification, denitrification and decomposition, thereby controlling the movement of nitrogen through the soil ecosystem. Modern research shows that biofertilizers can influence these microbial nitrogen transformations. Li et al. (2023) identified microbial groups and genetic functions associated with nitrogen cycling in biofertilizer-amended soil, demonstrating that plant responses can be connected to changes occurring within the microbial community.

Phosphorus: Unlocking the Locked Nutrient

Phosphorus is another essential plant nutrient. However, much of the phosphorus present in soil may occur in forms that are not readily available to plants. Certain microorganisms can produce organic acids, enzymes and other metabolites that help transform poorly available phosphorus into forms that plants can utilize. These microorganisms are commonly referred to as phosphate-solubilizing microorganisms. The importance of such microbial processes is particularly relevant because simply adding more phosphorus fertilizer does not necessarily mean that all of it will become available to plants. Microbial nutrient mobilization therefore represents an opportunity to improve nutrient-use efficiency rather than relying only on increasing fertilizer application.

Potassium and Micronutrients

Microorganisms can also influence the availability of potassium and micronutrients such as zinc and iron. Some microorganisms release organic acids or other compounds capable of interacting with mineral surfaces and releasing nutrients. Others produce siderophores that bind iron and influence its availability. Thus, microorganisms can act as biological nutrient managers, helping transform nutrients from relatively unavailable forms into forms that plants can access.

Plant Growth-Promoting Microorganisms: Tiny Partners with Big Effects

Not all beneficial microorganisms work simply by supplying nutrients. Some influence plant growth through biochemical interactions. Plant growth-promoting rhizobacteria (PGPR) are microorganisms that colonize plant roots or the surrounding rhizosphere and promote plant growth through one or more mechanisms. They may produce plant-growth-regulating substances, improve nutrient acquisition, influence root architecture, produce siderophores, contribute to stress tolerance or interact with other beneficial microorganisms.

Recent research in groundnut provides an excellent example. Eswaran et al. (2023) isolated and characterized *Pseudomonas fluorescens* and *Bacillus subtilis* from the groundnut rhizosphere and evaluated them as microbial bio stimulants. The researchers conducted both pot and field experiments and found that PGPR consortium treatments significantly improved growth, photosynthetic pigments, nodulation, leghaemoglobin, yield attributes and seed nutrient enrichment compared with the uninoculated control.

This finding is particularly interesting for oilseed agriculture because it demonstrates that beneficial microorganisms are not merely laboratory curiosities. Their effects can also be investigated under field conditions.

4. When Microbes Work Together

An important lesson emerging from microbiome research is that microorganisms rarely function in isolation.

Soil contains thousands of interacting microbial species. Some compete for nutrients, some cooperate, and others produce compounds that influence the growth or activity of neighbouring organisms. This has led to increasing interest in microbial consortia, in which two or more beneficial microorganisms are combined to provide complementary functions.

A recent study by Rotoni et al. (2025) provides an excellent example. The researchers examined interactions between arbuscular mycorrhizal fungi (AMF), their associated microbiome and plant-growth-promoting bacterial strains in chrysanthemum. They found that AMF-associated treatments increased root surface area, root diameter, root volume and biomass. This study illustrates an important principle: Sometimes the whole microbial community can be more important than a single microorganism.

The future of biofertilizers may therefore move increasingly from individual strains toward carefully designed microbial communities or synthetic microbial communities **(SynComs)**.

5. Microbes Helping Crops Face Stress

Agriculture is increasingly challenged by drought, salinity, heat and other environmental stresses. Soil microorganisms may contribute to plant resilience under these conditions.

One particularly interesting example comes from saline agriculture. Shan et al. (2023) developed a biofertilizer based on halotolerant microorganisms and evaluated its effects on rice under saline conditions. Their study addressed the problem that long-term soil salinization can cause nutrient imbalance, soil degradation and changes in microbial diversity.

ISSN: 3049-2289

The importance of such research is increasing because climate variability and soil degradation can expose crops to multiple stresses simultaneously. Beneficial microorganisms may influence root growth, nutrient acquisition and physiological responses, potentially helping plants maintain productivity under unfavourable conditions.

However, microbial inoculants should not be considered a universal solution to every stress. Their effectiveness depends on crop genotype, soil type, native microbial communities, temperature, moisture, nutrient status and environmental conditions. This is why locally adapted and scientifically validated microbial technologies are particularly important.

6. Can Microbes Replace Chemical Fertilizers?

A common question is whether biofertilizers can completely replace chemical fertilizers. The answer is more complicated than a simple yes or no.

Plants require adequate quantities of essential nutrients, and microbial inoculants cannot automatically supply all nutrients in all agricultural situations. Instead, microorganisms should be viewed as biological partners that can complement balanced fertilizer management.

Therefore, the more realistic future is not necessarily:

Chemical fertilizers vs. microorganisms

but rather:

Balanced fertilizers + beneficial microorganisms + good soil management.

7. The Microbiome: Moving Beyond Individual Microbes

Traditional microbiology often required scientists to isolate microorganisms and grow them in the laboratory. Although culture-based techniques remain extremely important, they cannot capture the full diversity of microorganisms present in soil because many microorganisms are difficult to culture under standard laboratory conditions.

Modern molecular techniques have changed this situation. Methods such as 16S rRNA sequencing, ITS sequencing, metagenomics, metatranscriptomics and other omics approaches allow researchers to investigate microbial communities at much greater depth. Metagenomics is particularly exciting because it can provide information about the genetic potential of entire microbial communities.

Instead of asking only:

"Which microorganisms are present?"

researchers can begin asking:

"What functions can this microbial community perform?"

This functional perspective is especially relevant to soil fertility because nutrient cycling, decomposition and plant-growth promotion depend on microbial activities rather than simply on the presence of particular species.

8. Plants May Also Choose Their Microbial Partners

Perhaps one of the most exciting developments in plant microbiome research is the recognition that plants themselves differ in their ability to interact with microorganisms. Different crop varieties can recruit different microbial communities. This raises an important possibility: *could crop breeding consider not only plant traits but also plant–microbe interactions?*

Zhao et al. (2025) investigated this idea using seven potato cultivars with different levels of what the researchers termed microbiome-interactive traits (MITs). In field experiments, cultivars with stronger microbiome-interactive traits showed better performance than the commercial cultivar used for comparison. Below-ground biomass was positively associated with these traits, while biological management enhanced interactions among different microbial groups.

This research suggests a fascinating direction for agriculture. In the future, breeders may not select plants only for yield, disease resistance or drought tolerance. They may also consider how effectively a crop variety interacts with its beneficial microbial partners. In other words, we may eventually breed plants together with their microbiomes.

9. Managing the Invisible Farmers

If microorganisms are our invisible agricultural workforce, they need a healthy working environment.

Agricultural practices can strongly influence soil microbial communities. Organic matter inputs, crop rotation, irrigation, fertilization, tillage and pesticide use can all influence the microbial environment. Maintaining soil organic matter is particularly important because microorganisms depend on carbon sources for energy.

Crop rotation can also influence microbial communities because different crops have different root systems, nutrient requirements and root exudates. A rotation is therefore not simply a sequence of crops above ground it is also a sequence of changing biological environments below ground.

The next stage of agricultural microbiology may be more sophisticated than simply producing a packet of biofertilizer containing one microbial strain.

Future microbial technologies may combine:

Beneficial microorganisms + microbial consortia + metagenomics + soil testing + crop genetics + precision nutrient management.

Such approaches could allow agricultural scientists to identify which microbial functions are missing or insufficient in a particular soil and then develop targeted biological interventions.

10. Challenges Ahead

Despite the enormous potential of beneficial microorganisms, several challenges remain.

A microbial inoculant that performs well in a laboratory or greenhouse may not always provide the same benefits in farmers' fields. Native microbial communities may compete with introduced organisms. Soil pH, temperature, moisture and nutrient availability can influence microbial establishment. Therefore, field validation is essential.

Another challenge is maintaining the quality and consistency of microbial products. The identity, viability, population density, formulation, shelf life and compatibility of microorganisms must be carefully evaluated.

Conclusion

The soil beneath an agricultural field may appear quiet, but it is never truly silent. Billions of microorganisms are continuously decomposing organic matter, transforming nutrients, interacting with roots and influencing plant growth. These microorganisms are the invisible farmers of agriculture.

The message is clear: sustainable agriculture is not only about managing the visible crop. It is also about managing the invisible biological community that supports it. The future farmer may therefore have another workforce to manage not with tractors or machinery, but with knowledge of microbial diversity, soil health, plant–microbe interactions and microbiome function.

The next agricultural revolution may be happening beneath our feet. And the workers have been there all along.

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Smart Vegetable Production Systems: A Sustainable Pathway For Future Agriculture

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Vegetables are an essential component of a healthy diet and an important source of income for millions of farming families. However, vegetable cultivation is becoming increasingly challenging because of irregular weather conditions, water scarcity, rising input costs, declining soil quality, labour shortages, pest and disease problems and changing market requirements.

These challenges require a new approach to vegetable cultivation that can increase productivity while conserving natural resources. Smart vegetable production provides such an approach by combining modern technology with scientific crop management.

Smart production does not simply mean using expensive machines or advanced equipment. It means using available information and technology to make better decisions about irrigation, nutrition, crop protection, environmental management and harvesting. Precision irrigation, sensors, Internet of Things (IoT), artificial intelligence (AI), protected cultivation, remote sensing and automated fertigation are some of the important components of this approach.

What is Smart Vegetable Production?

Smart vegetable production is a technology-supported, information-based and resource-efficient production system in which crop management decisions are adjusted according to actual crop and environmental requirements.

In conventional farming, the same amount of water or fertilizer may be applied across an entire field. In a smart system, information about soil moisture, temperature, humidity, crop growth and weather conditions can be used to determine where, when and how much input is required.

The basic principle is:

“Right input, right quantity, right time and right place.”

This approach can help farmers reduce wastage, improve crop performance and increase the efficiency of valuable resources.

Smart Irrigation for Water-Efficient Vegetable Production

Water management is one of the most important aspects of vegetable production. Excess irrigation may cause nutrient leaching, root problems and unnecessary water loss, while insufficient irrigation can reduce growth and yield.

Drip irrigation provides water close to the root zone and is particularly suitable for many vegetable crops. Its efficiency can be further improved by integrating soil-moisture sensors and automatic controllers.

A moisture sensor can provide information about the moisture status of the root zone. Based on this information, irrigation can be scheduled according to crop requirement rather than following a fixed timetable.

The combination of drip irrigation, soil-moisture monitoring, mulching and fertigation can create an efficient water-management system for vegetable cultivation.

Smart drip irrigation and moisture-based water management in vegetable production.

Smart Fertigation and Nutrient Management

Balanced nutrition is essential for obtaining high yield and good-quality vegetables. Excessive fertilizer application not only increases cultivation costs but may also adversely affect soil and water resources.

Smart nutrient management focuses on supplying nutrients according to crop growth stage and actual requirement. Soil testing provides the foundation for determining nutrient needs, while fertigation allows soluble nutrients to be delivered through irrigation water.

In protected cultivation, automated fertigation systems can regulate irrigation frequency and nutrient concentration more precisely. This can improve nutrient-use efficiency and reduce wastage.

A sustainable nutrient-management programme should integrate:

- ❖ Soil testing
- ❖ Organic manures and soil amendments
- ❖ Recommended fertilizers
- ❖ Drip fertigation
- ❖ Crop-stage-specific nutrient application
- ❖ Regular monitoring of crop growth

- ❖ Smart Greenhouses and Protected Vegetable Cultivation

Protected cultivation has significant potential for high-value vegetable production. Polyhouses, greenhouses and shade-net structures can provide protection from extreme environmental conditions and create a more favourable growing environment. Modern protected structures can be equipped with sensors for monitoring temperature, relative humidity, soil moisture and other environmental parameters. Automated ventilation, irrigation and fertigation can then be operated according to predefined crop requirements.

Smart protected cultivation system for high-value vegetable crops.

Crops such as tomato, coloured capsicum, cucumber, lettuce and cherry tomato can benefit from controlled production environments. Properly managed protected cultivation can improve crop uniformity, quality and production efficiency.

Artificial Intelligence in Vegetable Production

Artificial Intelligence is emerging as a promising technology for modern agriculture. AI systems can process large amounts of information obtained from sensors, cameras, weather stations and farm records. In vegetable production, image-based technologies can assist in identifying visible symptoms of diseases, insect damage and nutritional disorders. AI-supported systems can also help in crop growth monitoring, yield estimation and early identification of crop stress.

For example, a camera-based monitoring system may capture repeated images of a crop. Changes in leaf colour, canopy development or visible symptoms can then be analysed to identify potential problems.

However, AI should be considered a supporting technology rather than a substitute for farmer knowledge and scientific expertise. Field verification remains important before taking major management decisions. Drones and Remote Sensing. Agricultural

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drones provide a rapid method for observing crop conditions over larger areas. Cameras mounted on drones can capture detailed images that may reveal variations in crop growth, water stress and damaged areas.

Figure 3. Drone-based crop monitoring for precision vegetable production.

Remote sensing can help identify specific portions of a field that need attention. This can support site-specific irrigation, nutrient management and crop protection. The use of drones can also reduce the time required for crop inspection and provide useful information for farm-level decision-making.

Smart Pest and Disease Management

Pest and disease management is a major component of vegetable production. Excessive and unnecessary pesticide use can increase production costs and may have adverse environmental consequences.

Smart production systems can strengthen Integrated Pest Management (IPM) by combining field scouting with weather information, pheromone traps, sticky traps, disease forecasting and digital image analysis. Early identification of a problem allows farmers to take timely action. Biological control, resistant varieties, sanitation, cultural practices and need-based chemical applications should be integrated for sustainable crop protection.

The objective should be: “Prevent the problem where possible and control it only when necessary.”

Hydroponics and Soilless Vegetable Production

Urbanisation, declining availability of cultivable land and water scarcity have increased interest in hydroponics and other soilless production systems.

In hydroponic cultivation, plants receive water and nutrients through a carefully managed nutrient solution. Sensors can monitor parameters such as pH, electrical conductivity, temperature and humidity.

Figure 4. Hydroponic vegetable production for efficient use of land and water.

Soilless systems can be useful for leafy vegetables and selected high-value crops. They provide opportunities for controlled production and efficient use of space, although initial investment, technical knowledge, energy requirements and system maintenance need careful consideration.

Benefits of Smart Vegetable Production

Smart vegetable production can provide several advantages:

1. **Efficient Use of Water-** Precision irrigation can reduce unnecessary water application and improve water-use efficiency.

2. **Better Nutrient Management-** Fertigation and crop monitoring can improve nutrient-use efficiency and reduce fertilizer wastage.

3. **Improved Crop Monitoring-** Sensors, cameras and drones can provide timely information about crop health and environmental conditions.

4. **Reduced Input Wastage-** Inputs can be applied according to actual crop requirements rather than uniformly.

5. **Better Crop Quality-** Balanced nutrition and controlled environmental conditions can contribute to improved quality and uniformity.

6. **Reduced Labour Requirement-** Automation can reduce the need for repetitive manual operations.

7. **Climate Resilience-** Protected cultivation and precise environmental management can help crops cope with several climatic stresses.

8. **Improved Farm Profitability-** Efficient resource use, better crop quality and timely decision-making can improve economic returns.

Making Smart Technology Accessible to Farmers

Technology adoption should be practical and economically feasible. Small and marginal farmers may not be able to immediately invest in sophisticated automated systems.

A gradual approach can be more suitable:

Drip irrigation → Mulching → Soil testing → Fertigation → Moisture sensors → Weather-based advisories → IoT monitoring → Automation and AI

This stepwise model allows farmers to adopt technologies according to their needs, knowledge and financial capacity. Farmer training, demonstrations, custom hiring services and institutional support can further encourage the adoption of smart technologies.

Future Prospects

The future of vegetable cultivation is expected to become increasingly data-driven. AI-based crop diagnosis, automated irrigation, smart fertigation, greenhouse automation, drone monitoring, robotic operations and digital farm management systems are likely to become more accessible. The integration of renewable energy with smart irrigation and protected cultivation can further improve sustainability. Digital platforms may also help farmers maintain production records, monitor input costs, estimate yields and make better marketing decisions.

However, the future of smart farming should focus not only on advanced technology but also on affordability, simplicity, local suitability and farmer acceptance.

Conclusion

Smart vegetable production systems represent an important pathway towards sustainable and resilient agriculture. The integration of precision irrigation, smart fertigation, sensors, IoT, artificial intelligence, protected cultivation, remote sensing and integrated pest management can help farmers produce quality vegetables while using water, fertilizers, energy and other resources more efficiently.

The success of smart vegetable farming will depend on selecting appropriate technologies according to crop, climate, soil, farm size and economic conditions. Combining farmers' traditional knowledge with modern scientific tools can create a practical and sustainable production system.

The future of vegetable farming is not simply about producing more vegetables—it is about producing better vegetables with fewer resources, greater efficiency and greater sustainability.

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Remote Sensing and Sensors used for different applications (Globally)

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Introduction

A watershed can be defined as all stream flow originated in the area, drained towards a common outlet. Which helps in understand mechanism of runoff, erosion, sediment transport and groundwater recharge etc. however, watershed assessment requires information on terrain, drainage, rainfall, vegetation, soil, surface water and buildup area over period of time across the space (Suresh 2023). Traditional methods often costly, difficult to access inaccessible area and all above, limitation of repetition of observation. In contrast, remote sensing though it is costly, but remove all limitations of traditional method observe (Chawla et al., 2020).

Remote sensing (RS) can be defined as tool to obtain information about an object, area or phenomenon without being in direct physical contact with it. Basically its principle based on the measurement of reflected or emitted electromagnetic radiation from the particular object (NASA, 1997). For example, a satellite sensor records the electromagnetic response of a watershed, and distinguish them between water bodies, forest, agriculture, barren surfaces and settlements through their different spectral signatures (Nandgude et al., 2026a). Thus, RS converts the physical characteristics of watershed into measurable digital information that can be analyzed by using Geographic Information system such as ArcGIS, Google Earth Engine etc.

History begins from nineteenth century, where, in 1958, Gaspard Felix Tournachon, popularly known as Nadar, obtained an aerial photograph of small village near Paris from hot air balloon, demonstrating landscape could be observed from above rather than only from the ground. During the early twentieth century, aircraft replaced balloon as more stable platform for mapping, surveying and military reconnaissance. First and second world war accelerate the development of photographic method, infrared sensing and radar, while, civilian applications such as agriculture, forestry, geology and cartography and environmental monitoring progressed subsequently (GTC, 2021).

Today, remote sensing has progressed from conventional aerial photographs to multispectral, hyperspectral, thermal, microwave, synthetic aperture radar, LiDAR, UAV and high resolution satellite observation. Satellite such as Landsat and Sentinel does frequent monitoring which helps to detect both gradual and sudden changes in watersheds (Nandgude et al., 2026b). Sentinel-1 SAR valuable for flood mapping as radar observes day and night. Hence, significance of RS for watershed assessment has therefore expanded from simple mapping to integrated watershed analysis (NASA, 2019). Digital elevation model derived from RS, supports drainage extraction, stream order analysis, slope and relief, delineation of watershed and sub-watershed (Rokade et al., 2026). Multitemporal satellite images can detect changes in land use/land-cover (LULC), vegetation and water bodies, while rainfall and other remotely sensed datasets can provide additional inputs to hydrological modelling. Recent research shows that the combination of RS, GIS, Hydrological modelling, cloud computing and artificial intelligence is being used to assess runoff, evapotranspiration, erosion, groundwater, water quality and flood risk (Nandgude et al., 2026).

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In conclusion, remote sensing has evolved from an experimental method of photographing the Earth from balloons into an integrated technology for watershed assessment and management. Its ability to provide spatially continuous, repetitive and multi-source information makes it particularly useful for understanding how topography, drainage characteristics, land-use change and hydrological hazards interact within a watershed. The increasing integration of RS with GIS, machine learning and hydrological models is creating new opportunities for scientifically informed and sustainable watershed planning (Patel et al., 2026).

Components of Remote Sensing

Remote sensing acquires information about earth surface without direct physical contact, primarily by detecting reflected or emitted electromagnetic radiation (EMR). Components of RS consist of Energy Sources or Illumination, Sensor, Interaction with Target / Earth's Surface Object, Data receiver (ground station), data processing system, data dissemination and application. All these components are as shown in fig. 1. First component is an energy source used to provide electromagnetic radiation, Mostly, Sun is used as primary and natural source of energy in passive remote sensing. Solar radiation travels through the atmosphere and reaches earth's surface. While in active remote sensing, sensor itself act as source of energy. Second, these radiation interacts with the atmosphere and earth's surfaces such as vegetation, water, soil and buildings, which, absorb, reflect and emit radiation. Third is a sensor, usually mounted on satellite or aircraft. It detects the radiation reflected or emitted from earth surface and records in the form of digital data. Next, fourth component is receiver located at ground station, where they receive the information transmitted by satellite or any other sensor platform and stored for further processing. Fifth one is geographical information system software installed units i.e. Computer and other accessories. Which receives data and converts raw data into useful images, maps and other human comprehensive format. Finally, the processed information is distributed to users for practical applications.

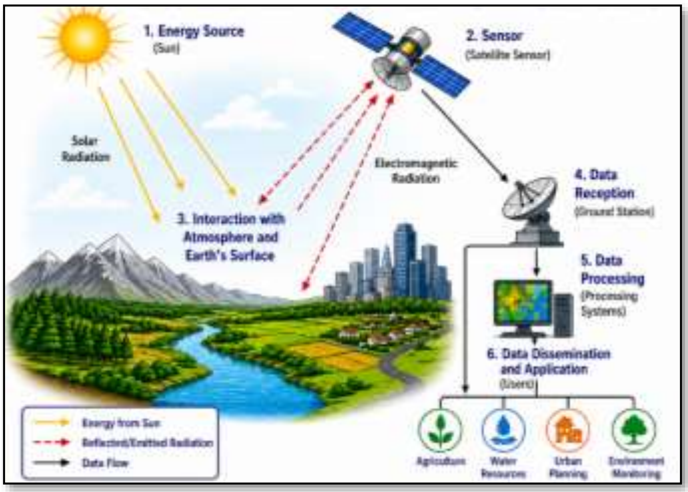

Fig. 1. Components of Remote Sensing

Types of Remote Sensing

Based on the source of light there are two types of remote sensing as given below and shown in fig. 2

1. Active remote sensing
2. Passive remote sensing

1. **Active Remote Sensing -** They have their own source of light or illumination. Particular, it actively sends a pulse and measures the backscatter, reflected to the sensor.
2. **Passive Remote Sensing -** Passive remote sensors measure reflected sunlight emitted from the Sun. Prime source of light is SUN.

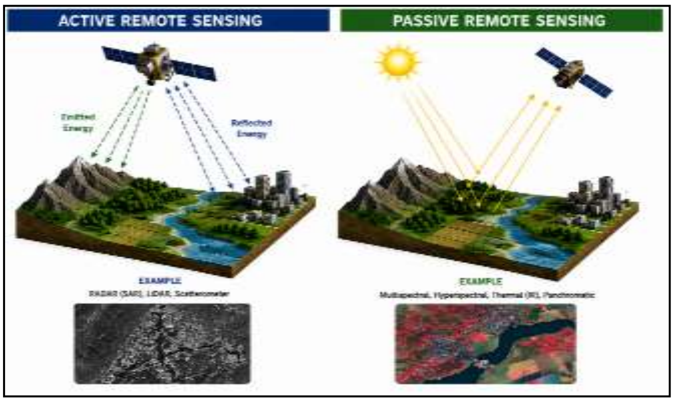

Fig. 2. Types of Remote Sensing

ISSN: 3049-2289

Applications of Remote Sensing

1. Rainfall estimation and hydrological monitoring.
2. Snow and glacier mapping for snowmelt runoff forecasting.
3. Irrigation water management and identification of potential irrigable lands.
4. Assessment of reservoir sedimentation and storage capacity changes.
5. Watershed planning, management, and conservation.
6. Disaster monitoring and management, including floods, droughts, and other hazards.
7. Water quality assessment and monitoring of aquatic resources.
8. Groundwater assessment, exploration, and potential zone mapping.
9. Planning and implementation of developmental activities using geospatial information.
10. Infrastructure planning, development, and monitoring.
11. Environmental monitoring and sustainable resource management

Table 1: List of Sensor Used Globally for Various Applications

Sensor Name	Platform	Type of Sensor	Major Application / Use	Reference
Landsat MSS	Landsat-1 to 5 satellites	Multispectral optical sensor (Visible–NIR)	Land cover mapping, agriculture, vegetation monitoring, environmental change detection	Goward et al., (2006)
Landsat TM	Landsat-4/5 satellites	Multispectral optical sensor (VNIR, SWIR, Thermal IR)	Vegetation mapping, land-use classification, hydrology, soil studies	Xue & Su (2017)
Landsat ETM+	Landsat-7 satellite	Multispectral + Panchromatic + Thermal sensor	Land-cover change, urban expansion, forest monitoring	Wulder et al., (2019)
Landsat OLI/TIRS	Landsat-8/9 satellites	Operational Land Imager + Thermal Infrared Sensor	LULC mapping, crop monitoring, surface temperature, drought assessment	Chaves et al., (2020)
MODIS	Terra and Aqua satellites	Multispectral optical + Thermal sensor (36 bands)	Global vegetation monitoring, fire detection, climate studies, ocean monitoring	Justice et al., (2002)
ASTER	Terra satellite	VNIR + SWIR + Thermal Infrared sensor	Mineral exploration, geological mapping, DEM generation, land surface temperature	Abrams, M. (2000)
Sentinel-2 MSI	Sentinel-2A/B satellites	Multispectral optical sensor with red-edge bands	Precision agriculture, vegetation health, land cover classification, water monitoring	Drusch et al., (2012)
Sentinel-1 SAR	Sentinel-1 satellites	C-band Synthetic Aperture Radar (active microwave)	Flood mapping, soil moisture, glacier monitoring, deformation studies	Torres et al., (2012)
SPOT HRV/HRG	SPOT satellite series	High-resolution optical multispectral sensor	wetland, forest, water, fire, and land-cover monitoring,	Poulin et al., (2010)
AVHRR	NOAA polar-	Optical and thermal radiometer	Climate monitoring, vegetation index generation, long-term	Tucker et al., (2005)

	orbiting satellites		ecosystem studies	
VIIRS	Suomi-NPP and NOAA-20 satellites	Visible and Infrared Imaging Radiometer	Fire monitoring, vegetation dynamics, ocean colour, atmospheric studies	Xiong et al., (2016)
PALSAR	ALOS satellite	L-band Synthetic Aperture Radar	Forest biomass estimation, deformation monitoring, land cover mapping	Rosenqvist et al., (2007)
LiDAR	Airborne/UAV/Ground platforms	Active laser ranging sensor	3D mapping, forest structure, DEM generation, urban modelling	Lefsky et al., (2002)
Hyperspectral Sensors (EnMAP/PRISMA/AVIRIS)	Airborne and satellite platforms	Hundreds of narrow spectral bands	Mineral identification, crop stress, species mapping, water quality	Ghamisi et al., (2017)

Conclusion

Remote sensing plays an important role in understanding and monitoring the Earth's surface by combining sensors, platforms, data collection, and image analysis techniques. Both passive and active remote sensing methods provide valuable information for different environmental and resource management applications. Various sensors, such as optical, thermal, microwave, LiDAR, and hyperspectral systems, are used depending on the specific requirements of studies related to agriculture, water resources, forestry, disasters, and environmental changes. Choosing the right sensor based on its capabilities helps generate accurate and reliable information, supporting better planning, monitoring, and decision-making for sustainable resource management.

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AGRICULTURE BULLETIN

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Soil Degradation in India: Scenario, Status, Symptoms and Pathways to Sustainable Management

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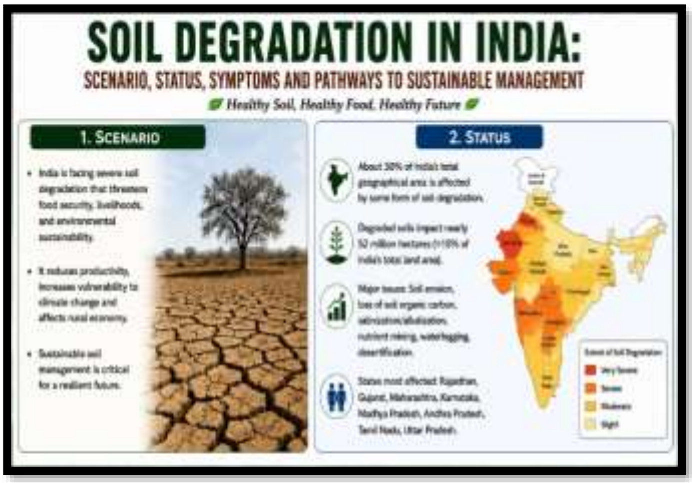
Soil forms the fundamental base of terrestrial life, supporting nearly 95 per cent of global food production while regulating water cycles, storing carbon and sustaining biodiversity. In India, an agrarian economy, progressive soil degradation driven by water and wind erosion, nutrient imbalance, declining organic carbon, salinization, intensive cultivation and climate extremes poses a serious threat to food security and environmental stability. Approximately 30 per cent of the country's geographical area (about 97 million hectares) is estimated to be affected by land degradation. Water-induced erosion accounts for nearly 68 per cent of total soil loss. Visible symptoms include topsoil depletion, reduced crop yields, increased frequency of floods and droughts, gully formation, sedimentation of water bodies and loss of soil biodiversity. This article examines the current scenario and status of soil health in India, identifies key symptoms and drivers of degradation, and outlines integrated sustainable solutions encompassing conservation agriculture, watershed management, agroforestry, soil-health improvement measures, climate-resilient practices and community participation. Strengthening ongoing government programmes such as the Soil Health Card Scheme, PMKSY and NMSA, coupled with digital monitoring tools, is essential for restoring soil productivity and securing long-term agricultural sustainability.

Introduction

Soil is far more than a medium for plant growth; it is a living, dynamic natural resource that underpins food systems, regulates hydrological processes, sequesters atmospheric carbon and maintains the biological diversity of terrestrial ecosystems. Globally, healthy soils support the production of the vast majority of food consumed by humans. Yet this critical resource is under mounting pressure. Unsustainable land-use practices, intensive agriculture, deforestation, mining, urban expansion and the growing influence of climate change are accelerating the rate of soil degradation worldwide.

India, with its predominantly agrarian economy and dense rural population, is particularly vulnerable. Fertile alluvial plains, productive black soils and diverse agro-ecological zones have historically sustained high levels of agricultural output. However, decades of intensive cultivation, imbalanced fertiliser use, declining organic matter, over-extraction of groundwater and extreme weather events have progressively undermined soil quality across large parts of the country. The loss of productive topsoil not only reduces crop yields but also diminishes the



capacity of landscapes to buffer floods, recharge aquifers and support biodiversity. Restoring and protecting soil health has therefore become an urgent national priority linked directly to food security,

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climate resilience and sustainable development goals.

2. Global and National Scenario of Soil Degradation

International assessments indicate that nearly one-third of the world's soils are moderately to highly degraded. Climate variability, characterised by intense rainfall events interspersed with prolonged dry spells, together with continued expansion of intensive farming systems, continues to drive erosion and fertility decline on a global scale.

In the Indian context, water and wind remain the principal agents of soil erosion. Studies, including research associated with the Indian Institute of Technology Delhi, suggest that rainfall and surface runoff account for approximately 68 per cent of total soil erosion, establishing water as the dominant erosive force. The problem is especially acute in flood-prone plains, steep Himalayan and north-eastern hill slopes, and semi-arid regions of western and central India. States such as Rajasthan, Maharashtra, Odisha, Gujarat, Assam, Meghalaya, Jharkhand, Bihar and Uttarakhand report significant erosion-related land degradation, with consequent declines in agricultural productivity and heightened environmental vulnerability.

3. Current Status of Soil Health in India

Recent estimates suggest that during 2025–26 nearly 30 per cent of India's geographical area equivalent to roughly 97 million hectares is affected by various forms of land degradation and soil erosion. The fertile topsoil layer, rich in organic matter and plant nutrients, is being lost at an alarming rate through the combined action of heavy monsoon rains, floods, wind, deforestation and inadequate land management.

India possesses a wide range of soil types alluvial, black (vertisols), red, laterite, desert, forest and mountain soils each with distinct characteristics and management requirements. While many regions continue to support high agricultural productivity, a growing number of areas exhibit clear signs of deterioration: declining soil organic carbon, nutrient imbalances (particularly secondary and micronutrient deficiencies), rising salinity and sodicity in irrigated tracts, soil acidity in high-rainfall zones, and physical degradation through compaction and crusting.

On a positive note, advances in remote sensing, Geographic Information Systems (GIS), digital soil mapping and artificial intelligence are enabling more precise identification of degradation hotspots and better targeting of interventions. Parallel government programmes are expanding the reach of scientific soil management practices across the country.

4. Symptoms of Soil Degradation

Healthy soil is characterized by good physical structure, adequate moisture-holding capacity, balanced nutrient status and a rich community of soil organisms. When degradation sets in, several diagnostic symptoms become evident:

- Progressive loss of fertile topsoil through sheet, rill and gully erosion by water or through wind action.
- Declining levels of soil organic carbon and reduced availability of both macro- and micronutrients.
- Stagnation or decline in crop yields and farm income despite continued or increased input use.

- Increased incidence and severity of floods, droughts and landslides in affected landscapes.
- Formation of gullies, ravines and permanently barren patches.
- Accelerated sedimentation of rivers, reservoirs, ponds and irrigation canals, reducing their storage and conveyance capacity.
- Impaired groundwater recharge and declining water-table levels.
- Reduction in soil biological activity and diversity of beneficial microorganisms.
- Development or intensification of soil salinity, sodicity, acidity or compaction.
- Greater susceptibility of crops to climatic stresses, pests and diseases.

These symptoms collectively demonstrate that soil degradation is not merely an agronomic problem; it is a multi-dimensional environmental and socio-economic challenge.

5. Major Drivers of Soil Degradation

Both natural processes and anthropogenic activities contribute to the observed decline in soil quality:

- High-intensity rainfall and unchecked surface runoff, especially on sloping lands.
- Strong winds in arid and semi-arid zones leading to aeolian erosion.
- Deforestation, forest degradation and recurrent forest fires.
- Unsustainable agricultural practices, including excessive tillage, monocropping and residue removal.
- Overgrazing of pasture and common lands.
- Mining, quarrying and large-scale infrastructure development.
- Rapid urbanisation and conversion of agricultural land.
- Inappropriate irrigation practices resulting in waterlogging and secondary salinization.
- Climate change, which amplifies the frequency and intensity of extreme weather events.

6. Sustainable Solutions for Soil Conservation and Restoration

Arresting and reversing soil degradation requires a multi-pronged strategy that integrates scientific knowledge, ecological principles and active community involvement.

6.1 Sustainable Agricultural Practices

Adoption of conservation agriculture (minimum or zero tillage, permanent soil cover and crop diversification), integrated nutrient management, organic farming, green manuring and balanced fertiliser application based on soil-test recommendations can simultaneously improve soil structure, organic carbon stocks and nutrient-use efficiency.

6.2 Afforestation and Agroforestry

Increasing vegetative cover through tree planting, shelterbelts, contour plantations and well-designed agroforestry systems reduces the erosive impact of rain and wind, enhances biodiversity and provides additional income streams to farming households.

6.3 Watershed and Water Management

Construction of check dams, contour bunds, graded bunds, farm ponds, percolation tanks and other rainwater-harvesting structures slows runoff, promotes infiltration and reduces sediment loss. Integrated watershed development remains one of the most effective landscape-scale approaches to soil and water conservation.

6.4 Soil Health Improvement Measures

Regular soil testing under the Soil Health Card programme, widespread use of compost, vermicompost, biofertilisers and crop residues, and correction of micronutrient deficiencies are essential

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for restoring the biological and chemical fertility of soils.

6.5 Climate-Resilient Land Management

Promotion of climate-smart agricultural practices including drought- and flood-tolerant varieties, efficient irrigation (drip and sprinkler systems), residue mulching and diversified cropping systems enhances the adaptive capacity of farming systems to climatic extremes.

6.6 Scientific Monitoring and Digital Tools

Continued investment in satellite-based monitoring, drone surveys, GIS-based decision-support systems and digital soil maps enables real-time assessment of erosion risk and more precise allocation of conservation resources.

6.7 Community Participation and Capacity Building

Long-term success depends on the active engagement of farmers, local institutions, educational organisations and civil-society groups. Awareness campaigns, farmer field schools and participatory planning processes are indispensable for scaling up sustainable land management.

7. Key Government Initiatives

The Government of India has put in place a comprehensive policy and programmatic framework to address soil degradation and promote sustainable agriculture. Important ongoing initiatives include:

- Soil Health Card Scheme – providing farmers with soil-test-based nutrient recommendations.
- Pradhan Mantri Krishi Sinchayee Yojana (PMKSY) – expanding irrigation coverage and improving water-use efficiency.
- National Mission for Sustainable Agriculture (NMSA) – promoting climate-resilient and resource-efficient farming systems.
- Integrated Watershed Management Programme and subsequent watershed development schemes.

- Afforestation and Green India Mission activities.
- Riverbank stabilisation and flood-control projects.
- Promotion of organic and natural farming practices.
- Digital soil mapping and erosion-risk assessment programmes.

Collectively, these programmes aim to enhance soil fertility, conserve natural resources, raise agricultural productivity and support sustainable rural livelihoods.

8. Conclusion

The evidence on the scenario, status and symptoms of soil degradation in India leaves little room for complacency. Productive soils are being lost at a rate that threatens long-term food security, water security, biodiversity and climate resilience. Soil degradation is no longer a purely agricultural issue; it is a central challenge for environmental sustainability and rural prosperity.

Reversing this trend demands coordinated action by governments, research institutions, extension systems, farmers and civil society. Scaling up proven practices conservation agriculture, watershed management, agroforestry, balanced nutrition, digital monitoring and community-based approaches offers

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a practical pathway toward restoring degraded lands. Protecting and regenerating India's soils today is an investment in the food, water and environmental security of future generations. The time for decisive, collective action is now.

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