ISSN: 3049-2289

AGRICULTURE BULLETIN

A Monthly Publication on Agriculture Trends

Volume-2 Issue-3 March 2026

AGRICULTURE BULLETIN

A Monthly Publication on Agriculture Trends

ISSN: 3049-2289

CONTENT

ISSN: 3049-2289

CONTENT

ISSN: 3049-2289

AGRICULTURE BULLETIN
ISSN: 3049-2289

RBI's Revised Guidelines on Priority Sector Lending: A Comprehensive Overview

Suraj Kumar Shoundik
CM (Research), SBA, Gurugram

The Reserve Bank of India (RBI) has consistently emphasized the importance of channelling credit to specific sectors of the economy that have a significant impact on inclusive growth and employment generation. These specific sectors known as the 'priority sector', often face challenges in accessing adequate and timely financial assistance. To ensure a continuous and enhanced flow of credit to these vital areas, the RBI periodically reviews and revises its guidelines on Priority Sector Lending (PSL).

The latest iteration of these guidelines, effective from April 1, 2025, marks a significant step towards fostering greater financial inclusion and aligning lending practices with the evolving needs of the Indian economy.

The primary objectives of PSL are:

Promoting Financial Inclusion:

- Primary aim of PSL was to made credit available to the under-banked segments of the population, including small and marginal farmers, women, and weaker sections.
- It helps to bridge the credit gap in areas where formal financial institutions may not be present or accessible.
- By making credit available to these sectors, PSL promotes financial inclusion and helps in the economic empowerment of marginalized communities.

Supporting Economic Growth:

- It helps in the development of key sectors such as agriculture, MSMEs and education, which are vital for the overall economic growth of a nation including employment generation and providing livelihoods to a large population.
- PSL stimulates economic activities, creates employment opportunities and enhances productivity through financial support to these sectors,
- It also helps to reduce income inequality and regional disparities by promoting balanced development across different sectors and regions. It encourages lending in credit-deficient regions of the country.

Achieving Social Objectives:

- Achieving social objective goals such as promoting education, healthcare, and housing for all.
- By directing credit towards these sectors, PSL contributes to the overall well-being and development of society.
- It also encourages innovation and entrepreneurship by supporting startups and other emerging businesses.
- To facilitate credit flow to sectors like education, housing, social infrastructure, and renewable energy, which have a direct impact on social and economic well-being.

Liquidity Management for Banks:

- The banks use PSLCs (Priority Sector Lending Certificates) to guard against shortfalls and help banks manage their cash flows better.
- It is used by the Banks to meet their PSL targets, allowing them to trade their excess lending to other banks that have not met their targets.

ISSN: 3049-2289

Over the years, the PSL guidelines have been refined to address emerging challenges and align with national development goals. The current revision builds upon the existing framework with several key enhancements.

Revised PSL Guidelines (w.e.f 01.04.2025)

The revised guidelines, issued under the powers conferred by the Banking Regulation Act, 1949, introduce several significant changes across various aspects of PSL. These changes aim to make PSL more effective, inclusive, and responsive to the current economic landscape.

The increase in the sub-target for 'Advances to Weaker Sections' across all bank categories underscores the RBI's commitment to enhancing credit access for the most vulnerable segments of the population. The main aim of revision in the overall PSL target for UCBs is to create a more uniform and potentially more challenging but achievable target for these institutions.

Target/Sub-targets for priority sector at a glance:

Categories	Domestic Commercial Banks (excl. RRBs & SFBs) & Foreign Banks with 20 branches and above	Foreign Banks with less than 20 branches	Regional Rural Banks	Small Finance Banks
Total Priority Sector	40 per cent of ANBC as computed in para 6 above or CEOBSE, whichever is higher.	40 per cent of ANBC as computed in para 6 above or CEOBSE, whichever is higher; out of which up to 32% can be in the form of Export Credit and not less than 8% can be to any other priority sector	75 per cent of ANBC as computed in para 6 above or CEOBSE, whichever is higher. However, lending to Medium Enterprises, Social Infrastructure and Renewable Energy shall be reckoned for priority sector achievement up to 15 per cent of ANBC only	75 per cent of ANBC as computed in para 6 above or CEOBSE, whichever is higher.
Agriculture	18 per cent of ANBC or CEOBSE, whichever is higher. Within this target, 14 percent is prescribed for Non-Corporate Farmers (NCFs), out of which a target of 10	Not applicable	18 per cent ANBC or CEOBSE, whichever is higher. Within this target, 14 percent is prescribed for NCFs, out of which a target of 10 percent is prescribed for SMFs.	18 per cent of ANBC or CEOBSE, whichever is higher. Within this target, 14 percent is prescribed for NCFs, out of which a target of 10 percent is prescribed for SMFs.

	percent is prescribed for SMFs			
Micro Enterprises	7.5 per cent of ANBC or CEOBSE, whichever is higher	Not applicable	7.5 per cent of ANBC or CEOBSE, whichever is higher	7.5 per cent of ANBC or CEOBSE, whichever is higher
Advances to Weaker Sections	12 percent of ANBC or CEOBSE, whichever is higher	Not applicable	15 per cent of ANBC or CEOBSE, whichever is higher	12 percent of ANBC or CEOBSE, whichever is higher

PSL targets/ sub-targets for Urban Cooperative Banks (UCBs):

Categories	Targets as a percentage of ANBC or CEOBSE, whichever is higher
Total Priority Sector	60%
Micro Enterprises	7.50%
Advances to Weaker Sections	12%

Source: RBI

1. Expansion of the 'Weaker Sections' Category:

The definition of 'Weaker Sections' has been broadened to include transgenders, in addition to the existing categories:

- Small and Marginal Farmers
- Distressed farmers indebted to non-institutional lenders
- Artisans, village and cottage industries
- Self-Help Groups (SHGs)/ Joint Liability Groups (JLGs) members
- Person belonging to Scheduled Castes (SCs) and Scheduled Tribes (STs)
- Persons with disabilities
- Minority communities as notified by the Government of India from time to time
- Individual women beneficiaries up to ₹2 lakh (this limit is not applicable to UCBs under the revised guidelines, indicating a further push for lending to women)

Expanding the definition of weaker sections reflects a more inclusive approach, ensuring that credit reaches a wider spectrum of marginalized communities, including transgenders, thus promoting greater financial inclusion. The removal of the loan cap for individual women beneficiaries for UCBs is a significant step towards empowering women entrepreneurs and individuals.

2. Enhanced Loan Limits under Priority Sector:

Several loan limits under the priority sector categories have been enhanced to better reflect the current costs and financing needs:

- **Education Loans** limit has been increased to ₹25 lakh per individual from existing ₹20 lakh, including vocational courses.

ISSN: 3049-2289

- **Housing Loans:** Loan limits for housing have been increased to provide greater financial access, particularly in Tier III to Tier VI cities, aiming to boost affordable housing. Specific revised limits vary based on the population of the centre.
- **Renewable Energy:** Loan limits for renewable energy projects have been increased to ₹35 crore from existing Rs 30 crore per borrower for purposes like power generators and public utilities. The limit for individual households for renewable energy remains at existing level of ₹10 lakh.
- **Social Infrastructure** loan for projects such as setting up schools, drinking water facilities, and sanitation facilities has been increased to ₹8 crore per borrower from existing ₹5 crore.

Increasing these loan limits acknowledges the rising costs in these sectors and aims to provide more substantial financial support, thereby encouraging greater investment and development in crucial areas like education, affordable housing, renewable energy, and social infrastructure.

3. Addressing Regional Credit Disparities:

To address the issue of uneven credit deployment across the country, the revised guidelines introduce a system of differential weightage to priority sector lending based on the per capita credit flow to districts.

Districts with comparatively lower per capita credit flow will be assigned a higher weightage (125%) for PSL achievement whereas Districts with comparatively higher per capita credit flow will be assigned a lower weightage of 90%.

This mechanism aims to incentivize banks to increase lending in credit-deficient districts, thereby reducing regional disparities in credit access and promoting more balanced economic development across the country. The RBI will likely notify the list of districts with high and low per capita credit flow periodically.

4. Ineligibility of Loans Against Gold Jewellery Acquired from NBFCs:

The revised guidelines clarify that loans taken against gold jewellery acquired by banks from Non-Banking Financial Companies (NBFCs) (i.e. Investment by banks in securitisation notes with loans against gold jewellery originated by NBFCs) will not be considered under the priority sector lending category.

This move is intended to ensure that priority sector funds are directed towards genuinely needy sectors and prevent the reclassification of existing NBFC portfolios as PSL.

Implications and Potential Impact of the Revised Guidelines

The revised PSL guidelines are expected to have a wide-ranging impact on various stakeholders in the Indian financial ecosystem:

- **Banks:** Banks will need to realign their lending strategies and internal processes to comply with the revised targets, enhanced loan limits, and the new definition of weaker sections. The differential weightage for lending in credit-deficient districts will require a strategic shift in their geographical focus. Enhanced monitoring will necessitate more robust data collection and reporting mechanisms.
- **Borrowers in Priority Sectors:** The increased loan limits will provide greater financial assistance to individuals and entities in sectors like education, housing, renewable energy, and social infrastructure. The expanded definition of weaker sections will bring more marginalized communities under the umbrella of priority sector lending, improving their access to credit. The

ISSN: 3049-2289

restrictions on excessive charges on small loans will benefit vulnerable borrowers.

- **Economy:** The revised guidelines are expected to contribute to more inclusive and balanced economic growth. Increased credit flow to agriculture, MSEs, education, affordable housing, renewable energy, and social infrastructure will have a positive multiplier effect on employment generation, social development, and environmental sustainability. The focus on reducing regional credit disparities can lead to more equitable development across the country.
- **Financial Inclusion:** The inclusion of transgenders in the weaker sections category and the removal of the loan cap for women beneficiaries for UCBs are significant steps towards greater financial inclusion of marginalized groups.

Challenges and Way Forward

While the revised PSL guidelines are a progressive step, their effective implementation may present certain challenges:

- **Achieving the enhanced targets for weaker sections:** Banks may need to develop specific strategies and outreach programs to effectively lend to newly included categories and ensure that the increased targets are met in substance and not just in numbers.
- **Lending in credit-deficient districts:** Banks might face operational challenges and perceived higher risks in lending to districts with low per capita credit flow. Incentives and support mechanisms may be needed to encourage greater lending in these regions.
- **Monitoring and ensuring the end-use of funds:** Banks will need to strengthen their monitoring mechanisms to ensure that PSL loans are used for the intended purposes and to mitigate the risk of asset quality deterioration.
- **Balancing PSL obligations with profitability:** Banks need to strike a balance between meeting their PSL obligations and maintaining their profitability and asset quality. Innovative lending models and risk mitigation strategies will be crucial.

Moving forward, effective communication and collaboration between the RBI, banks, and other stakeholders will be essential for the successful implementation of the revised PSL guidelines. Capacity building and awareness programs for both bankers and borrowers in the priority sectors can further enhance the impact of these guidelines. The RBI may also need to periodically review the guidelines based on their on-ground impact and evolving economic realities to ensure they continue to serve their intended purpose of fostering inclusive and sustainable growth.

In conclusion, the RBI's revised guidelines on Priority Sector Lending, represent a significant step towards a more inclusive, equitable, and sustainable financial ecosystem in India. By enhancing loan limits, expanding the scope of weaker sections, focusing on emerging sectors like renewable energy, and addressing regional disparities, these guidelines aim to channel credit more effectively to the segments of the economy that need it the most, thereby contributing to the nation's overall development objectives.

Source: RBI Master direction on PSL, 2025

AGRICULTURE BULLETIN
ISSN: 3049-2289

Application of Droplet Digital PCR (ddPCR) for Detection and Quantification of Genetically Modified Organisms (GMOs): An Indian Perspective

Monika Singh and Shruti Sinha
Division of Genomic Resources, ICAR-National Bureau of Plant Genetic Resources, Pusa Campus, New Delhi – 110 012

The stringent regulation of genetically modified (GM) food crops and derived commodities in India have heightened the need for accurate, reliable, and highly sensitive methods of GM detection followed by the quantification, wherever necessary. Among the available technologies, droplet digital Polymerase Chain Reaction (ddPCR) has emerged as a powerful platform for GMO detection and quantification. High level of precision, sensitivity, and robustness makes this technology relevant in the Indian context for regulatory, industrial, and research requirements in GM detection. Moreover, this technology can be efficiently employed for the precise detection of genome edited plants, thereby serving as a robust molecular tool for regulatory verification and compliance assessment under the biotechnology regulatory framework in India.

Introduction to ddPCR Technology

Droplet digital PCR (ddPCR) is a nucleic acid quantification method that partitions each reaction into thousands to millions of droplets, with PCR amplification occurring independently within each droplet (Košir *et al.*, 2019). Instead of measuring fluorescence across an entire reaction (as in quantitative real-time PCR), ddPCR directly counts the number of positive and negative droplets. This enables absolute quantification of target DNA sequences without the use for standard curves, hence the reference materials are not required. Because it effectively turns each droplet into a tiny reaction vessel, ddPCR greatly improves sensitivity, minimizes the influence of inhibitors, and enhances reproducibility. These features are essential when analyzing processed food matrices, mixed seed lots, or samples containing extremely low levels of GM material.

In GMO analysis, ddPCR allows amplification of the template DNA molecules present in each droplet and workflow used is almost similar to those for TaqMan® probe-based real-time PCR assay (**Fig. 1**). After amplification, once the droplets are passed through the detector that measure fluorescence intensity, GMO screening targets such as *P-35S* promoter or *T-nos* terminator can be detected. Each droplet is then classified as GM positive (containing amplified GM targets) or GM negative (in the case of no amplification for GM targets). Furthermore, ddPCR allows absolute quantification without the use for a standard curve where the concentration of GM target is estimated on the basis of the number of positive and total droplets using Poisson distribution. Internationally, ddPCR has been used as an emerging tool for detection of GM as well as genome edited plants (Demeke and Eng, 2025; Fraiture *et al.*, 2022; Košir *et al.*, 2019)

The key advantages of ddPCR for GMO detection and quantification are as follows:

1. ***Absolute quantification:*** ddPCR provides an absolute count of target GMO copies per input sample without the need for running standard curves, making this technique ideal GMO quantification, particularly in the case where GMO standards are not available.
2. ***Unparalleled precision:*** The massive sample partitioning allows the comparative measurement of small fold differences in target GMO copy numbers among the test samples.

ISSN: 3049-2289

3. ***Increased signal-to-noise ratio:*** High-copy templates and background noises are diluted, effectively enriching template concentration in target-positive partitions, allowing for the sensitive detection of low level presence of GMO target with precision.
4. ***Simplified quantification:*** Neither calibration standards nor a reference is required for absolute quantification, thereby making it an open-ended approach with potentially broader application across the systems.

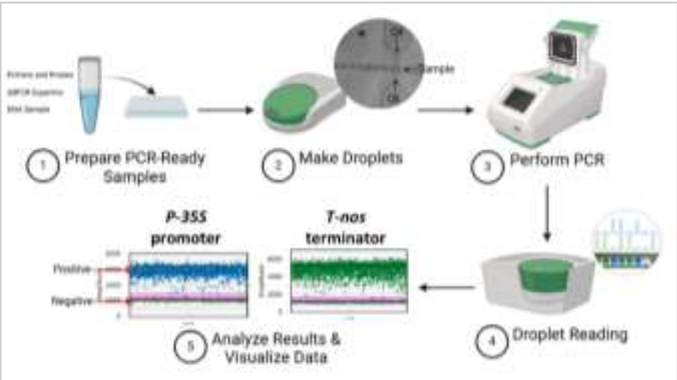


Fig. 1. Workflow of ddPCR in GM detection (made using BioRender software - https://www.biorender.com/)

Potential of ddPCR for GMO detection in the Indian context

The ddPCR has immense potential for GMO detection in India, which can be summarized as follows:

1. **Regulatory purpose:** India regulates the research, release, import, and use of genetically engineered organisms under a structured regulatory and biosafety framework led by the authorities such as the Genetic Engineering Appraisal Committee (GEAC) under the Ministry of Environment, Forest and Climate Change, the Food Safety and Standards Authority of India (FSSAI), and agencies involved in trade, customs, and agriculture. These bodies rely on the molecular testing to ensure that food and agricultural products comply with national guidelines and labelling requirements. In this context, ddPCR acts as a precise analytical tool that enables GM detection laboratories to accurately determine whether or not, a seed lot or food product contains transgenic sequences or any unauthorized GM event, and whether the GMO content exceeds any applicable thresholds *(although so far no GMO labelling threshold prevails in the country)*. The capacity of this technology to detect transgenic sequences even when present in trace amounts is remarkable particularly for regulatory surveillance, especially at ports of entry where imported commodities such as soybean, canola and maize are routinely screened.
2. **Seed purity testing:** India's seed industry, one of the largest in the world, requires high standards of genetic purity for both GM and non-GM crops. For crops such as cotton, maize and soybean, the presence or absence of specific GM events must be confirmed to maintain varietal integrity, meet certification standards, and satisfy market requirements based on the regulatory requirement and the approval status. ddPCR offers exceptional accuracy while quantifying transgene copy number or estimating the proportion of GM seeds in a bulk sample. This technology is particularly useful for distinguishing heterozygous versus homozygous plants in breeding programs and for validating the presence of stacked traits. Because ddPCR provides absolute quantification, it minimizes ambiguity in purity assessment and supports seed producers in meeting national and international quality norms.
3. **Monitoring unauthorized and low-level presence of GMOs:** One of the key and continuing challenges worldwide including India, is the management of unauthorized or adventitious presence of GMOs in supply chain. Even with stringent regulatory control, traces of transgenic DNA may appear in non-GM consignments due to cross-pollination, seed

mixing, or global trade. The ability of ddPCR to detect and precisely quantify very small amounts of target DNA, often below the typical detection limits of conventional PCR, makes it especially valuable for such cases. The technology henceforth strengthens the biosafety compliance by providing high-confidence results that support enforcement actions, risk assessments, and regulatory decision-making.

4. **Food quality assurance:** Due to rising demand and import of processed food products, food manufacturers and distributors in India face greater requirements to verify the GMO status of ingredients for informed consumer choice. Ingredients derived from crops such as soybean, maize, sugar beet, or canola may carry GMO depending on their source country. ddPCR can be applied in quality-control pipelines to screen raw materials, intermediate products, and finished goods. For companies exporting food products to markets with strict GMO labelling rules (such as the European Union), ddPCR provides a reliable tool to demonstrate compliance with foreign regulatory limits. Its robustness with processed and complex matrices is particularly useful for verifying GMO content in products such as oils, bakery premixes, and animal feed formulations.

5. **Research and development applications**: ddPCR can be applied for characterization of transgenic plants as well as genome edited plants. In the early stages of transgenic plant development, ddPCR enables accurate enumeration of transgene copy number, which is important for selecting stable, single-copy insertion events. Moreover, ddPCR supports studies on gene expression (via quantification of cDNA), and assists in the analysis of gene editing outcomes, including the detection of small insertions, deletions, or editing efficiencies in genome edited plants. Because plant genomes can be large and complex, the precision of ddPCR provides researchers with a reliable method for evaluating molecular characteristics without the variability inherent in other quantitative techniques.

Conclusion

ddPCR represents a major advancement in molecular diagnostics for GMO detection and quantification. In India, its application spans regulatory compliance, seed testing, research, food industry quality assurance, and surveillance against unauthorized GM events. As global trade grows and biotechnology continues to evolve, the role of ddPCR in ensuring biosafety, transparency, and consumer confidence will only become more significant. Its precision and reliability as well as open-ended strategy make it one of the most valuable tools in country's molecular testing landscape, supporting both scientific innovation and regulatory integrity.

References

Demeke T., Eng M. (2025) Detection of soybean GMO events using two multiplex droplet digital PCR assays. *J. AOAC Int*. 108 (1): 23-28.

Fraiture M.A., Guiderdoni E., Meunier A.C., Papazova N., Roosens N.H.C. (2022) ddPCR strategy to detect a gene-edited plant carrying a single variation point: Technical feasibility and interpretation issues. *Food Cont*. 137:108904.

Košir A.B., Demšar T., Štebih D., Žel J., Milavec M. (2019) Digital PCR as an effective tool for GMO quantification in complex matrices. *Food Chem.* 294: 73-78.

AGRICULTURE BULLETIN
ISSN: 3049-2289

Innovative Technologies Reshaping the Biocontrol of Fungal Vascular Pathogens

Madhaiyan Sakthivel[1*] and Madhu J[2]
Ph.D. Scholar, Division of Plant Pathology, ICAR-Indian Agricultural Research Institute, New Delhi, India- 110012.

Fungal vascular pathogens are among the most destructive plant pathogens in annual and perennial crops, causing systemic infections and major yield losses. Conventional control measures are often ineffective due to deep vascular colonization. This has created an urgent need for sustainable and innovative biocontrol strategies. Traditional biocontrol agents (BCAs) are now being strengthened by advanced tools such as meta-omics, microbiome engineering, nanotechnology, artificial intelligence (AI), genome editing, RNA interference (RNAi), and functional peptides. These technologies improve understanding of plant–microbe–pathogen interactions, enable targeted suppression, and enhance BCA efficacy. Integration of these approaches marks a major shift toward precision, sustainable management of vascular fungal diseases.

Introduction

Fungal vascular pathogens are fungi that infect the vascular systems of plants, primarily the xylem, causing wilting and other diseases. These include *Fusarium oxysporum* and several species belonging to the genera *Veriticillium*, *Ceratocystis* and *Ophiostoma*, which cause significant diseases such as Fusarium and Verticillium wilts or Dutch elm disease. These pathogens are considered highly destructive because of their capacity to invade the host vascular system and spread systemically throughout the plant. As a result, vascular diseases can cause substantial yield reductions, with reported losses ranging from 10% to 50% of total crop production in affected systems (Cabanas and Mercado-Blanco, 2025).

The life cycle of fungal vascular pathogens typically begins with the survival of the fungus in the soil or plant debris through specialized dormant structures such as chlamydospores (*Fusarium*), microsclerotia (*Verticillium*), or other resistant spores (coremia), thick-walled mycelium. When conditions become favourable, they germinate and infect plant roots through wounds or natural openings. The fungus then colonizes the xylem, blocking water transport and causing wilting. Finally, it produces spores or resting structures that return to the soil, completing the cycle. Most of the symptoms caused by vascular wilt pathogens develop in acropetal direction: from bottom to top. Epinasty is the primary disease symptom, followed by flaccidity, chlorosis, vascular browning, and necrosis of the terminal leaflets. Despite the availability of chemical and biological control measures, the management of vascular fungal pathogens remains challenging due to their systemic colonization, persistence in soil, and genetic variability. Traditional biocontrol approaches have shown promise but their field efficacy is often inconsistent under diverse environmental conditions. In this context, the integration of emerging technologies is redefining the scope of biological control, offering precision, improved delivery, and enhanced pathogen suppression. This article highlights the cutting-edge technological advancements that are transforming the biocontrol of fungal vascular pathogens.

Traditional Biocontrol of Fungal Vascular Pathogens

Trichoderma spp., particularly *T. harzianum* and *T. atroviride*, represent some of the most successful BCAs reported against soil-borne vascular fungi. These fungi suppress pathogens through enzymatic degradation of fungal cell walls, competitive exclusion in the rhizosphere, mycoparasitism and activation of plant defense pathways, thereby enhancing overall plant resilience (Harman *et al.,* 2004) (Table 1).

Table 1. Traditional Biocontrol agents (BCAs) against fungal vascular pathogens with their mode of action

Biocontrol agents	Target pathogen	Mechanism of action / Function
Trichoderma spp. (*T. harzianum*, *T. atroviride*)	Vascular fungi (general)	Enzyme production (chitinases, glucanases), competition, ISR induction
Pseudomonas spp., *Paenibacillus* spp.	Vascular pathogens	Antibiotic production, siderophores, ISR/SAR induction, VOCs
Streptomyces spp.	*Fusarium* spp., *Verticillium* spp.	Antifungal compounds, enzymes, hyperparasitism, plant growth promotion
Clonostachys rosea (Mycoparasitic fungi)	*Verticillium dahliae*	Mycoparasitism (on mycelium and microsclerotia)
Arbuscular Mycorrhizal Fungi (e.g. *Rhizophagus irregularis*, *Funneliformis mosseae*)	*Verticillium*, *Fusarium*	Enhance plant immunity, nutrient uptake, improve plant health

Challenges of Fungal Vascular Pathogen Control

Controlling vascular fungal pathogens is challenging because they spend much of their life cycle hidden inside the plant. After entering the xylem, they become difficult targets for contact-based fungicides, which often fail to reach the infection site. In some cases, insect vectors such as *Scolytus* beetles directly introduce pathogens like *Ophiostoma ulmi* into the vascular tissues, making early intervention even more complicated (Hughes *et al.,* 2015). Additional reasons that make control difficult include,

1. **Systemic Colonization within the Xylem:** Once inside the plant, these fungi spread through the water-conducting xylem vessels, moving upward and colonizing the entire plant. This internal spread makes many contact fungicides ineffective because they cannot reach the pathogen deep within tissues.
2. **Persistent Resting Structures in Soil:** These pathogens form durable survival structures including chlamydospores, microsclerotia, thick-walled mycelia, that remain viable in soil for years, even over a decade in the case of *Verticillium* spp.
3. **Broad Host Range:** Many vascular pathogens can infect a wide variety of plant species. This reduces the efficacy of crop rotation and other cultural practices designed to break the disease cycle.
4. **High Genetic Variability and Adaptability:** Pathogens like *Fusarium oxysporum* and *Verticillium* species exhibit high strain-to-strain genetic diversity. They can quickly evolve new races or overcome plant resistance genes.
5. **Hidden Life Cycle Inside the Host:** Because much of the fungal lifecycle occurs inside the plant, early detection is difficult and infections are often only visible when the disease is already advanced.

Innovative Technologies on Biocontrol agents (BCAs)

Advanced tools such as meta-omics, microbiome engineering, nanotechnology, artificial intelligence, genome editing, RNA interference, and functional peptides are enabling more precise manipulation of microbial communities. These technologies enhance pathogen suppression, improve BCA efficacy and support controlled delivery systems for sustainable

ISSN: 3049-2289

vascular disease management (Cabanas and Mercado-Blanco, 2025) (Figure 1).

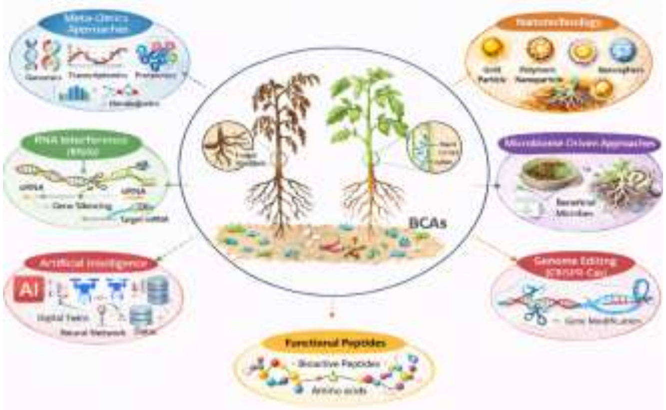


Figure 1. Emerging technologies for improving biocontrol agents (BCAs)

1. Meta-Omics Approaches in Biocontrol Optimization

Meta-omics approaches, including metabarcoding, metagenomics, metatranscriptomics, metaproteomics, and metabolomics, provide comprehensive insights into microbial communities and their functional roles in disease suppression (Ayaz *et al.,* 2023).

i. Metagenomics: culture-independent approach that enables rapid and precise detection of vascular pathogens directly from environmental samples. It also provides a broad understanding of plant–microbe interactions and supports the identification of antagonistic microorganisms for designing effective microbial consortia with enhanced disease-suppressive capacity.

ii. Metatranscriptomics: Looks at RNA expression in microbes during natural product synthesis and identifies genes that are actively expressed and tells us how and when microbes produce useful compounds.

iii. Metaproteomics: Finds enzymes involved in biosynthesis of natural products and also reveals regulatory mechanisms and how different conditions affect protein production. Metaproteomic analyses can reveal the functional relationships of plant–microbe and microbe–microbe interactions under specific environmental conditions.

iv. Metabolomics: Focuses on metabolites (end products of biochemical reactions), Identifies and quantifies natural products produced by microbes. Metabolomics offers valuable information on changes in metabolic profiles associated with plant pathogenesis that can affect plants, phytopathogens, and/or beneficial microbes.

2. Microbiome Engineering Approaches in Biocontrol

Microbiome engineering contemplates both the direct inoculation of exogenous beneficial microorganisms and the re-inoculation of autochthonous beneficial microorganisms enriched ex situ. Two distinct approaches including bottom-up and top-down approaches have been developed in plant microbiome engineering (Hu *et al.,* 2022).

1. Bottom-up approaches: Focuses on building or modifying the plant microbiome from individual or selected microbial strains upwards. Microbial systems engineered using the bottom-up approach are usually assembled using a limited number of members, which are also termed "synthetic microbial consortia". Four principles have been proposed to guide the design of such consortia, (i) control of intercellular interactions, (ii) control of spatiotemporal coordination, (iii) maintenance of robustness, (iv) prevention of biocontainment.

2. Top-down approach: This approach analyzes natural microbial communities and manipulates environmental or host factors to favor beneficial microbes through synthetic ecology. It uses enrichment, artificial selection, and directed evolution to enhance functional and resilient microbial communities.

3. Nanotechnology in Biocontrol

Combining biotechnology and nanotechnology to improve the effectiveness and sustainability of plant disease management may lead to advances at an unprecedented scale.

i. **Synthesis of Nanoparticles:** Green synthesis enables eco-friendly nanoparticle production using plant extracts, fungi, bacteria, algae, yeast, or marine sources. In biogenic synthesis, biological extracts reduce metal ions (e.g., Ag^{+}), while natural capping agents stabilize nanoparticles and prevent aggregation.

ii. **Loading of Biocontrol agents (BCAs):** Antimicrobial peptide, secondary metabolites and beneficial microbes are incorporated into or absorbed onto the nanoparticle surface. This step enhances stability against environmental stress, protection from premature degradation and sustained release at target site.

iii. **Encapsulation of beneficial microorganisms:** Enclosing BCAs or antifungal compounds within a nanocarrier matrix. The techniques including, ionic gelation (extrusion or cross-linking), spray-drying, and emulsion are most often used to encapsulate beneficial microorganisms (Balla *et al.,* 2022).

4. Artificial Intelligence in Biocontrol

Artificial intelligence (AI) involves the use of advanced computational algorithms that mimic aspects of human intelligence, enabling systems to learn, analyze complex datasets, detect patterns, and support decision-making (Russell and Norvig, 2010). Core branches of AI include machine learning for predictive modeling, computer vision for image-based disease detection, and natural language processing for extracting insights from scientific or field data.

i. Potential of AI Tools in Biological Control of Vascular Phytopathogenic Fungi: AI analyzes complex datasets (environmental factors, microbial communities, disease incidence) to detect patterns beyond conventional methods. It integrates real-time data to optimize and tailor BCA applications for specific field conditions.

ii. Early Detection, Accurate Diagnosis, Risk Prediction, and Infection Modelling: AI enables early detection of vascular fungi using image recognition, sensors, deep learning, and hyperspectral imaging even at asymptomatic stages. Predictive and infection models assess outbreak risks and simulate disease progression for timely BCA intervention.

iii. AI-Assisted Identification, Selection, and Optimization of BCAs: AI mines genomic, metagenomic, and ecological datasets to identify beneficial strains with antifungal traits and host compatibility. It optimizes microbial consortia, formulations, and delivery systems, improving precision and field efficacy.

iv. Predicting the Impacts of BCAs: AI simulates BCA performance under varying soil, climate, and crop conditions. This supports optimization of dosage, delivery methods, and application timing.

v. Simulating Plant–Pathogen–Biocontrol Interactions: AI models plant–pathogen–BCA interactions within vascular tissues, predicting competition and suppression dynamics. These virtual simulations refine strategies before field deployment, reducing risk and error.

5. Genome Editing approaches in Biocontrol

Genome editing (GE) consists of the modification (deletions, insertions, and replacements) of genomic DNA at specific target sites in a wide range of cell types and organisms (Xu *et al.,* 2020). Zinc finger nucleases (ZFNs), transcription activator-like effector nucleases (TALENs), and the RNA-guided CRISPR (Clustered Regularly Inter spaced Short Palindromic Repeats)-Cas (CRISPR-associated) nucleases systems are the three primary genome editing approaches. CRISPR-Cas Applications in Plant-Microbe Interactions are,

i. **Gene Editing:** CRISPR-Cas9 enables targeted gene knockout in beneficial bacteria like *Bacillus* spp., facilitating the study of genetic mechanisms that enhance plant fitness and resistance to pathogens.

ii. **Endophytic Microbial Functions:** Endophytic bacteria produce secondary metabolites that can induce plant defense mechanisms, contributing to disease resistance and promoting growth under stress conditions.

6. RNA Interference (RNAi) in Biocontrol

RNAi is a conserved post-transcriptional gene-silencing mechanism in eukaryotes that degrades mRNA or blocks translation, serving as a natural immune defense against foreign DNA. Spray-induced gene silencing (SIGS), host-induced gene silencing (HIGS), virus-induced gene silencing (VIGS), and microbe-induced gene silencing (MIGS) are innovative RNA interference (RNAi) techniques that have shown silence pathogen genes, enhancing resistance against vascular fungal pathogens (Rosa *et al.,* 2018).

- **SIGS**: Involves the direct application of dsRNA onto plant surfaces, which can lead to transient gene silencing in pathogens. Both plant and pathogen process dsRNA into siRNAs, which silence fungal virulence genes upon infection. This is a non-transgenic, eco-friendly method
- **VIGS**: A mycovirus is engineered to carry target gene segments. Infects *F. graminearum*, triggering its RNAi machinery to silence internal genes. It's like using a virus to make the fungus silence itself.
- **MIGS**: A beneficial fungus like *Trichoderma harzianum* is engineered to produce dsRNA targeting F. *oxysporum*. The dsRNA from T. *harzianum* is transferred to the pathogen during interaction, silencing virulence genes.
- **HIGS**: Involves the expression of dsRNA in host plants, targeting genes in pathogens. This method has been effective against various fungal pathogens, including *Verticillium dahlia*.
- **Fungal Transformants:** A vector (plasmid) with hairpin RNA (hpRNA) is inserted directly into the fungus (e.g., *Fusarium).* The fungus itself expresses dsRNA, which is processed into siRNA inside its own cells, leading to self-silencing of pathogenic genes.
- **Exogenous RNA (Liquid Culture):** dsRNA is added externally into fungal liquid cultures. Fungus takes up the dsRNA from the medium, which is processed into siRNA, silencing target genes

7. Functional peptides in Biocontrol

Functional peptides are short amino acid sequences (50-60 amino acids) derived from natural sources or synthesized artificially, exhibiting biological activities beyond nutrition (Li *et al.,* 2021). Antimicrobial peptides (AMPs) interact with membranes, receptors, or enzymes to exert antibacterial, antiviral, and antifungal effects against vascular fungal pathogens. Some of antimicrobial peptides derived from bacteria, seeds, fungi and plant with their mode of action against fungal vascular pathogens have mentioned in Table 2.

Table 2. Functional peptides for the control of phytopathogenic vascular fungi

Antimicrobial peptides	Source	Target fungi	Mode of action
Defensins	Petunia plant	F. *oxysporum* f.sp. *cubense*	Disrupt fungal membrane integrity
Surfactin A	*Bacillus subtilis* NH-100 and *Bacillus* sp. NH-217	F. *oxysporum*	Strong antifungal activity
Purothionin	Wheat endosperm	C. *fimbriata*	Antifungal activity

Some tools like Genome Editing, RNA interference, and functional peptides are the innovative, high-potential technologies yet to be fully implemented in biocontrol.

Future Perspectives

1. Synthetic Microbiome Engineering: The design and deployment of synthetic microbial consortia tailored to the plant vascular system could revolutionize biocontrol. These consortia would combine multiple beneficial traits like antagonism, biofilm formation, systemic colonization, and priming of plant immunity, providing long-lasting and robust protection.

2. Integration of Multi-Omics with AI for Predictive Biocontrol: Combining genomics, transcriptomics, proteomics, and metabolomics with AI/machine learning will allow, predictive modeling of pathogen outbreaks and selection or design of the most effective biocontrol agents for a specific crop-pathogen-soil-environment context.

3. Nanotechnology-Enabled Biocontrol Systems: Nanotechnology offers innovative platforms for enhancing the stability, delivery, and activity of biocontrol agents (BCAs) against fungal vascular pathogens. Nano-sensors embedded in soil or plant tissues to detect early signs of pathogen infection and trigger timely BCA application.

Conclusion

Emerging technologies are reshaping the future of biocontrol against fungal vascular pathogens. By integrating multi-omics, AI-driven prediction, genome editing, RNAi, nanotechnology, and functional peptides, researchers can develop precise, efficient, and environmentally responsible disease management systems. Although regulatory, scalability, and field-validation challenges remain, these innovations represent a transformative step toward resilient and sustainable agriculture.

References:

Ayaz, M., Li, C. H., Ali, Q., Zhao, W., Chi, Y. K., Shafiq, M., & Huang, W. K. (2023). Bacterial and fungal biocontrol agents for plant disease protection: Journey from lab to field, current status, challenges, and global perspectives. *Molecules*, *28*(18), 6735.

Balla, A., Silini, A., Cherif-Silini, H., Chenari Bouket, A., Alenezi, F. N., & Belbahri, L. (2022). Recent advances in encapsulation techniques of plant growth-promoting microorganisms and their prospects in the sustainable agriculture. *Applied Sciences*, *12*(18), 9020.

Cabanas, C. G. L., & Mercado-Blanco, J. (2025). Groundbreaking Technologies and the Biocontrol of Fungal Vascular Plant Pathogens. *Journal of Fungi*, *11*(1), 77.

Harman, G. E., Howell, C. R., Viterbo, A., Chet, I., & Lorito, M. (2004). Trichoderma species-opportunistic, avirulent plant symbionts. *Nature reviews microbiology*, *2*(1), 43-56.

Hu, H., Wang, M., Huang, Y., Xu, Z., Xu, P., Nie, Y., & Tang, H. (2022). Guided by the principles of microbiome engineering: Accomplishments and perspectives for environmental use. *Mlife*, *1*(4), 382-398.

Hughes, M. A., Smith, J. A., Ploetz, R. C., Kendra, P. E., Mayfield, A. E., Hanula, J. L., ... & Pernas, T. (2015). Recovery plan for laurel wilt on redbay and other forest species caused by *Raffaelea lauricola* and disseminated by *Xyleborus glabratus*. *Plant Health Progress*, *16*(4), 173-210.

Li, J., Hu, S., Jian, W., Xie, C., & Yang, X. (2021). Plant antimicrobial peptides: structures, functions, and applications. *Botanical Studies, 62*(1), 5.

Rosa, C., Kuo, Y. W., Wuriyanghan, H., & Falk, B. W. (2018). RNA interference mechanisms and applications in plant pathology. *Annual review of phytopathology*, *56*(1), 581-610.

Russell, S. J., & Norvig, P. (2010). Artificial Intelligence-A Modern Approach, 3rd ed.; Pearson: London, UK, 2010; 1151p.

AGRICULTURE BULLETIN
ISSN: 3049-2289

Artificial Intelligence ((AI) Transforming Indian Agriculture: Vision to Reality

Jambamma[1], B. K. Naganjali[2] and K.Shireesha[3]
Asst. Prof. (Ag. Eng.)[1], Assoc. Prof. (Agron.)[2], Asst. Prof. (Ag. Extn.)[3]
PJTAU-Hyderabad, Agricultural College Aswaraopeta-507301, B.Kothagudem

AI turns satellite imagery, weather, soil, and crop data into actionable farming advice, enabling precise decisions on irrigation, fertilizers, and pests to cut risks and boost efficiency.

Key uses

- **Soil Health Diagnostics**: Deep learning and image recognition analyze satellite/drone/farm images to detect nutrient deficiencies, speeding up lab testing.
- **Climate-Responsive Crop Monitoring**: AI predicts rainfall, temperatures, and extremes for advisories on sowing, irrigation, pests, and inputs. Satellites, drones, and sensors enable early pest/disease detection, aiding rainfed farmers.
- **Farm Mechanization Efficiency**: AI with drones/sensors optimizes machinery for weed removal, disease detection, harvesting, and grading. In horticulture, it offers 24/7 surveillance of high-value crops, reducing labor and inputs.
- **Price Realization for Farmers**: AI forecasts demand-supply using e-NAM, AGMARKET, Census, and Soil Health data, guiding crop choice, timing, and markets to improve incomes and avoid distress sales.

AI Transforming Indian Agriculture

AI networks now serve 1.8 million farmers across 12 states, improving market access and price discovery

Digital Agriculture Mission Progress

- 7.63 crore Farmer IDs created (target: 11 crore by 2026-27)
- 23.5 crore crop plots surveyed nationwide (Updated from 4.8cr IDs & 23.9cr plots in early 2025)

National Pest Surveillance System

- Covers 66 crops and 432+ pest types
- Real-time alerts to 10K,000+ extension workers
- Enables early pest detection and intervention

Figure 1. AI & AgriTech Innovation Ecosystem – 8 Strategic Pillars

Table 1. AI4AGRI-Partnership & Support Ecosystem in India

Host & Lead Partners	Government of Maharashtra - Department of Agriculture AIAIC, under MahaAgri-Al Policy 2025-2029; Ministry of Electronics & Information Technology (MeITY)--Official SateliteEvent, aligned with India Al	

ISSN: 3049-2289

	Mission & digital infrastructure	
Strategic Knowledge Partners	National & international universities, CGIAR centers, DPI experts, responsible AI & governance bodies, think tanks	
Global Development Partners	World Bank, Asian Development Bank, FAO, IFAD, IFC	
Industry & Technology Partners	AgriTech, vkach, Climate Tech, Telecom & Automation, Automation, Consulting firms, Input& Market linkage companies	
Investment & Capital Partners	VC, Impact & Climate Funds, Corporate Ventures, Sovereign Wealth, Development Finance, Agri-focused PE	
Community, Farmers & FPOs	FPOs, Women-led SHGs, Cooperatives, Civil society organizations	
Research, Innovation & Academic Partners	SAUS, IITS, IIMs, IISc, ICAR, CGIAR, Global Al Labs, Digital Agriculture & Climate Research Universities	
Media & Outreach Partners	Intemational & national media, Digital broadcast, Sector-focused publications, Agri & tech media	

Table 2. Empowering Farmers with AI: India's Flagship Initiatives

Kisan e-Mitra: A multilingual AI chatbot, has handled over 93 lakh queries as of December 2025, supporting 8,000+ daily interactions in 11 regional languages for farmer advisories.

Kharif 2025 AI monsoon pilot: This AI pilot delivered local monsoon onset forecasts via SMS to 3.88 crore farmers across 13 states, influencing 31–52% to adjust sowing and land preparation.

PMFBY WhatsApp Chatbot: The PMFBY chatbot streamlines crop insurance claims through WhatsApp, making processes faster and more transparent for farmers under the Pradhan Mantri Fasal Bima Yojana.

CROPIC AI Tool: CROPIC uses AI for real-time crop monitoring via drones and image analytics, enhancing pest detection, yield prediction, and insurance assessments in Indian fields. Similarly YES-TECH, PMFBY bots enhance insurance.

Bharat-VISTAAR AI Initiative: Proposed in Union Budget 2026-27, Bharat-VISTAAR is a multilingual AI platform integrating AgriStack portals with ICAR systems for unified farm data and advisories

Telangana's AI-Driven Agricultural Advisory System;

Saagu Baagu

- **2021 Khammam Chilli Pilot:** 21% yield increase, 11% higher prices, 9% lower inputs, 5% less fertilizer, ₹66,000/acre/cycle income boost
- **Oct 2023 Scale-up:** 500K farmers across 10 districts, 5 crops (7K+ chilli farmers)
- **Partnerships:** World Economic Forum (AI4AI/C4IR India), Bill & Melinda Gates Foundation, executed by Digital Green
- **Solutions:** CRISPR seeds, bioinputs, precision irrigation, AI credit tools, drone-satellite data
- Addresses: 40% post-harvest losses, climate risks for smallholder farmers

Telangana Drone Paddy Plantation Pilot

- **Objective:** Tackle severe labor shortages & rising cultivation costs
- **Technology:** Drones with seed boxes + 3-5 dispensing tubes for direct row sowing

ISSN: 3049-2289

- **Partners:** PJTSAU + Marut Drones via KVKs (Karimnagar, Adilabad, Kothagudem, Nalgonda)
- **Efficiency:** 1 acre in 15-20 minutes vs 12-14 laborers traditionally
- **Benefits:** No nursery needed, eliminates manual transplanting, major cost/time savings

KRISHI RASTAA – Telangana Soil Tech Revolution

- **Partnership:** Telangana Govt + Krishitantra
- **Technology:** Portable automated device tests 12 soil parameters in 30 minutes
- **Delivery:** Instant soil health reports + fertilizer recommendations via mobile app (secure login)
- **Benefits:** Higher input efficiency & productivity
  - Increased farmer income
  - Reduced fertilizer/water use
  - Less soil degradation
- **Goal:** Climate-resilient agriculture through intelligent nutrient management



ALU: Revolutionizing Telangana Land Planning

- **Technology:** Agricultural Land Understanding (ALU) + AMED APIs with AI/ML
- **Data Integration:**
  - Digitized cadastral maps (Telangana Remote Sensing Agency)
  - Record of Rights (RoR) from Revenue Dept.
  - Farmer data: land area, sowing schedules, crop history (Agriculture Dept.)
- **Capabilities:** Precise identification of farmers' operational landholdings
- **Benefits:** Data-driven decisions, effective monitoring, enhanced agricultural governance.

ISSN: 3049-2289

Farmer Producer Organisations (FPOs): The Future Cooperatives of Indian Agriculture

Sreelakshmi Vinodan
MSc student Punjab Agricultural University

Indian agriculture is largely dominated by small and marginal farmers who face numerous structural and market-related challenges. Farmer Producer Organisations (FPOs) have emerged as a transformative institutional mechanism to empower producers through collective action, aggregation, and professional management. By combining cooperative principles with corporate governance structures, FPOs aim to improve productivity, reduce transaction costs, enhance price realization, and strengthen rural livelihoods. This article explores the concept, structure, policy framework, benefits, challenges, and future potential of FPOs, positioning them as modern cooperatives capable of reshaping Indian agriculture.

Introduction

Agriculture remains the backbone of India's rural economy. However, nearly 86 percent of farmers in the country are small and marginal, cultivating less than 1.1 hectare of land. These farmers face persistent challenges such as high input costs, lack of access to technology, inadequate institutional credit, and limited bargaining power in markets. A long chain of intermediaries in agricultural marketing often reduces the producer's share in the final consumer price.

Collective organization offers a viable solution to these issues. Farmer Producer Organisations (FPOs) provide a structured platform through which producers can aggregate their resources and operate as business entities. The Small Farmers' Agribusiness Consortium was mandated by the Government of India to support state governments in promoting FPOs. Today, FPOs are widely recognized as the future cooperatives of Indian agriculture.

Concept and Structure of FPOs

A Farmer Producer Organisation is a legally registered entity formed by primary producers for undertaking business activities related to agricultural and allied sectors. It may be registered under the Companies Act as a Producer Company or under the Cooperative Societies Act of respective states.

Key features include:

- Formation by producers for farm or non-farm activities
- Legal registration and corporate identity
- Producers as shareholders
- Democratic governance through elected boards
- Profit-sharing with members and reinvestment of surplus

The ownership and control remain entirely with the farmer members. While external agencies may assist in formation and initial operations, management decisions are taken by representatives elected by members.

The economic foundation of FPOs lies in aggregation. By pooling produce and inputs, farmers achieve economies of scale, reduce transaction costs, and improve bargaining power in both input and output markets.

From Traditional Cooperatives to Modern FPOs

India has a rich cooperative history. Institutions such as Amul transformed the dairy sector through collective marketing and value addition. Similarly, Indian Farmers Fertiliser Cooperative Limited has

ISSN: 3049-2289

played a vital role in ensuring input security for farmers.

However, traditional cooperatives faced limitations including political interference, bureaucratic control, and weak financial management. FPOs evolved to address these concerns by incorporating professional management practices and operating under company law frameworks. They retain cooperative principles while ensuring transparency, accountability, and competitiveness.

Policy Framework: The 10,000 FPO Scheme

To strengthen farmer collectives, the Government of India launched the Central Sector Scheme for the formation and promotion of 10,000 FPOs. The scheme was inaugurated by Narendra Modi in February 2020 under the guidance of the Ministry of Agriculture and Farmers Welfare.

The scheme aims to:

- Enhance productivity and income
- Provide five-year handholding support
- Facilitate credit and market linkages
- Develop entrepreneurial skills

Major implementing agencies include the National Bank for Agriculture and Rural Development, National Cooperative Development Corporation, and National Agricultural Cooperative Marketing Federation of India.

Financial provisions include assistance up to ₹18 lakh per FPO, matching equity grants, and credit guarantee facilities up to ₹2 crore to ensure institutional credit accessibility.

Benefits of FPOs

Economic Benefits

FPOs enhance price realization and reduce input costs through collective bargaining. Studies indicate increased price realization by approximately 20–22 percent for members marketing through Producer Companies. Marketing costs are significantly reduced due to elimination of intermediaries.

Social Empowerment

FPOs promote inclusive participation, strengthen rural leadership, and encourage women and youth engagement in agribusiness activities.

Financial Inclusion and Technology Access

Through institutional linkages, FPOs improve access to credit, insurance, quality inputs, and modern technologies. Capacity-building initiatives strengthen managerial and entrepreneurial skills among members.

Challenges

Despite strong policy backing, FPOs face challenges such as:

- Limited professional management capacity
- Insufficient working capital
- Weak branding and value addition
- Member coordination issues
- Competition from established agribusiness firms

Continuous training, governance reforms, and stronger market integration are essential to overcome these constraints.

Future Prospects

For FPOs to become truly sustainable future cooperatives, the following steps are necessary:

- Digital marketing integration
- Strengthened value chains and branding
- Youth-led leadership models
- Climate-resilient agriculture adoption

ISSN: 3049-2289

- Export market linkages

A robust ecosystem involving government, financial institutions, academia, and private stakeholders will ensure long-term sustainability.

Conclusion

Farmer Producer Organisations represent a significant institutional innovation in Indian agriculture. By combining collective ownership with professional management, FPOs offer an effective mechanism to enhance farmers' income and strengthen rural economies. With sustained policy support and member-driven governance, FPOs have the potential to redefine the cooperative movement and lead Indian agriculture toward a more resilient and prosperous future.

References

Amul. (n.d.). *History and cooperative model documentation.*

Government of India. (2020). *Central Sector Scheme for Formation and Promotion of 10,000 Farmer Producer Organizations (FPOs).* Ministry of Agriculture and Farmers Welfare, New Delhi.

IFFCO. (n.d.). *Organizational overview and cooperative services.*

NAFED. (n.d.). *Role in strengthening agricultural marketing through FPOs.*

NABARD. (n.d.). *Farmer Producer Organisation promotion initiatives.*

NCDC. (n.d.). *Support framework for Farmer Producer Organisations.*

PricewaterhouseCoopers (PwC). (n.d.). *Impact Study: Enhanced realization of agriculture produce marketed through Producer Companies under Maharashtra Agricultural Competitiveness Project.*

SFAC. (n.d.). *Guidelines and operational framework for promotion of Farmer Producer Organisations.*

AGRICULTURE BULLETIN
ISSN: 3049-2289

Advanced Agronomic Interventions in Vegetable Production Systems

Mala Dasari Pavan[1] and *G Prameela[2]
[1]Department of Vegetable Science, IGKV, Raipur, Chattisgarh-492012
[2]Department of Agronomy, OUAT, BBSR, Odisha-751003

Increasing food demands, water scarcity, and climate change are among the challenges facing modern vegetable farming. Precise irrigation, fertigation, remote sensing, IoT, Unmanned aerial vehicle (UAV) and artificial intelligence are examples of cutting-edge techniques that improve production's resilience, efficiency and sustainability. Sensor data increases water efficiency by more than 200%, reduces irrigation by 63.8%, and enhances quality through fertilizer optimization. Mulching, rotation, and integrated pest management are examples of practices that improve both biodiversity and profitability. Precise monitoring, stress detection, and focused interventions are made possible by UAV imaging and AI analytics, which maximise yields and reduce waste, ensuring long-term viability in the face of global limits.

Introduction

A new age in vegetable farming is about to begin, one that will be influenced by creativity, science and technology in addition to hard work and tradition. Growers can no longer rely just on traditional methods due to the unpredictable effects of climate change, decreasing water resources and growing food demands. Rather, the cultivation of vegetables is being revolutionised by sophisticated agronomic interventions, such as drones, sensors, artificial intelligence, and precise irrigation and fertigation. These techniques provide more robust crops, healthier soils, and more intelligent resource usage in addition to increased yields. Modern agronomy is changing vegetable production into a system that can prosper in the difficult environment of today while protecting the future by fusing sustainability with profitability.

The Need for Advanced Agronomy in Modern Vegetable Farming

Modern vegetable farming needs sophisticated agronomic tactics to combat growing food demands, diminishing water supplies and intensifying climate change. This calls for precise, effective and environmentally friendly growth techniques. Precision technology, such as IoT sensors, remote sensing, artificial intelligence and big data analysis, is utilised in digital farming to facilitate ongoing monitoring and evidence-based crop management decisions. Drone-driven energy balance models produce correlations of $r = 0.98$ for net radiation and 0.85-0.92 for latent heat flow, confirming their superiority for agricultural water evaluation. Remote sensing techniques measure actual evapotranspiration with less than 10% error rates (RMSE 0.3 mm day^{-1}). Soil moisture sensors show $R^2 = 0.70$ and $r = 0.84$, confirming their usefulness in irrigation planning, whereas IoT systems achieve r^2 values of 1.0 (inside settings) and 0.9994 (outdoor) for tracking evapotranspiration. Big data initiatives improve pest management, watering, and nutrient application, increasing farm yield by 10-15%. While UAVs give precise, timely images for targeted reactions, platforms such as Landsat and Sentinel-2 satellites provide multispectral insights for extensive

ISSN: 3049-2289

vegetation surveillance. These cutting-edge agronomic techniques increase water efficiency, reduce resource abuse, guarantee yield stability, reduce costs, and prevent ecological harm, establishing technical advancement as essential for long-lasting, flexible vegetable systems that must contend with the current climate and resource constraints. (Fuentes *et al.*,2024).

Smart Water and Nutrient Management Techniques

In greenhouse vegetables, drip irrigation with automated fertigation maximises the use of water and nutrients by using sensors to keep soil moisture at 80-95% or 80-85% field capacity. This reduces irrigation by 24.3-63.8% (from 375-425 mm to 154-284 mm during 46-118 frequent applications), increases water productivity by 56.3-225.4%, and increases yields by 11.1-17.4%. Fertigation with 300 kg N, 50 kg P, and 550 kg K ha^{-1} increases efficiency (N: 43-55% to 62-78%; comparable for P/K), improves fruit quality (vitamin C +35.2-64.3%; sugars +21.7-37.8%), increases fine root growth (0-2 mm), and increases dry matter (8.9-21.1%). In general, water conservation, nutrient efficiency, improved roots, and higher yield/quality are guaranteed by sensor-integrated precision systems. (Wang *et al.*, 2024).

Climate-Resilient and Eco-Friendly Field Practices

Sophisticated agronomic strategies, like mulching, crop rotation, and integrated pest management (IPM)-combined with drip irrigation and fertigation, foster resilient, environmentally friendly vegetable farming systems. Studies across various crops reveal that drip fertigation elevates water use efficiency (e.g., 268.26 kg ha^{-1} mm^{-1} in onions, fivefold rise in cauliflower, 52% yield boost in eggplant) and cuts fertilizer waste (15-30% reduction in okra), while driving yield gains (149.36 q/ha in broccoli, 73.2 t/ha in cabbage, greater curd mass in cauliflower, 58.7% increase in tomatoes). These methods also curb disease outbreaks and nutrient runoff, evident in chillies and tomatoes, where fertigation lessened weed issues and leaching. Mulching retains soil moisture, rotation sustains fertility and disrupts pest lifecycles, and IPM lowers reliance on chemicals, all synergising with fertigation's accuracy. Collectively, they amplify profitability (benefit-cost ratios reaching 4.57 in broccoli and 2.99 in okra) and promote ecological balance, rendering vegetable production more efficient, productive, and sustainable. (Giram *et al.*,2023).

Digital Tools and Precision Technologies in Vegetable Production

Vegetable cultivation is undergoing significant transformation with the adoption of precision technologies such as sensors, drones, and artificial intelligence (AI), which enhance crop monitoring and optimize the efficient use of resources. Unmanned aerial vehicles (UAVs) equipped with advanced sensors—including red–green–blue (RGB), multispectral, hyperspectral, thermal, and light detection and ranging (LiDAR) cameras collect detailed information on crop growth, health status, and stress conditions. To evaluate plant vitality, nutrient health and water deficits in vegetable crops, these tools generate important vegetation indices, such as normalised difference vegetation index (NDVI), green normalised difference vegetation index (GNDVI), soil-adjusted vegetation index (SAVI), and normalised difference red edge index (NDRE). Weed mapping, plant counting, and accurate crop identification are all made possible by AI-driven image processed by deep learning and machine learning. AI systems achieved 96.46% location precision for chilli seedlings, convolutional

ISSN: 3049-2289

neural networks achieved about 95% accuracy for detecting spinach plants, and semi-supervised methods achieved about 90% for weed identification. Beyond detection, these improvements support timely corrective actions by identifying pests, illnesses, and abiotic challenges early. In the end, integrating sensors, UAVs, and AI analytics improves yields, resource utilisation, and ecological sustainability in vegetable production by optimising the use of fertilisers, pesticides, herbicides, and water. (Canicatti *et al*.,2024).

Economic Benefits and the Future of Vegetable Farming

Vegetable growers are seeing significant financial advantages and promising futures because of innovative agronomic techniques that make use of digital and precision technologies. UAVs, sensors, AI and IoTs are examples of innovations that enable farmers to make accurate, timely decisions by providing real-time data on crop growth, soil moisture, nutrient levels, and weather patterns. These systems save costs while maintaining or increasing yields by streamlining the application of inputs such as fertilisers, insecticides, herbicides, and irrigation. Growers prevent production declines and improve produce quality via early detection of crop stress, pests, diseases, and nutrient shortage. Transplanting, weed control, irrigation, and harvesting are examples of labour-intensive processes that can be automated to reduce labour requirements and increase productivity. As a result, operations see less waste, improved labour allocation, more accurate yield projections and increased profits. In vegetable systems, reduced chemical inputs and more intelligent resource management also promote environmental health. Adopting these technologies opens up important avenues for increased productivity, revenue, and long-term viability in modern vegetable agriculture in the face of growing global food demands due to population growth and limited farmland. (Samadi *et al*.,2025).

Conclusion

Precision, sustainability, and innovation are key components of the future of vegetable farming. From sensor-driven irrigation that conserves water to AI-powered crop monitoring that prevents losses, advanced agronomic practices are proving to be both economically rewarding and environmentally responsible. Farmers who adopt these technologies are not only increasing yields and profits but also contributing to ecological balance and long-term food security. As global demand for vegetables continues to rise, adopting these clever, climate-resilient strategies will be crucial.

Reference:

Canicattì, M, & Vallone, M. (2024). Drones in vegetable crops: A systematic literature review. *Smart Agricultural Technology*, *7*, 100396.

Fuentes-Penailillo, F., Gutter, K., Vega, R., & Silva, G. C. (2024). Transformative technologies in digital agriculture: Leveraging Internet of Things, remote sensing, and artificial intelligence for smart crop management. *Journal of Sensor and Actuator Networks*, *13*(4), 39.

Giram, K. S., Jadhav, S. B., Awari, H. W., & Ingle, V. K. (2023). Optimising irrigation and fertigation management for vegetables. *International Journal of Innovative Science and Research Technology, 8*(11), 2366, 2372.

Samadi, V. (2025). Empowering Precision Agriculture with Advanced Technology.

Wang, Q., Jia, Y., Pang, Z., Zhou, J., Scriber II, K. E., Liang, B., & Chen, Z. (2024). Intelligent fertigation improves tomato yield and quality and water and nutrient use efficiency in solar greenhouse production. *Agricultural Water Management*, *298*, 108873

AGRICULTURE BULLETIN
ISSN: 3049-2289

Disease Identification and Scoring of Plant Infection

Pranab Dutta*, Manihar Talukdar, Julia Thongam and Laimayum Mona Devi
School of Crop Protection, College of Post Graduate Studies in Agricultural Sciences,
CAU(Imphal), Umiam, Meghalaya – 793103, India.

Plant diseases cause huge economical losses emphasizing the need for accurate identification and assessment of plant diseases to enable timely management as well as to minimize crop damage. Plant disease identification and understanding key concepts such as Disease Incidence, Disease Severity, Percent Disease Index and various disease assessment or infection scoring scales is the first and foremost step in managing diseases. Quantification of diseases is important for estimating yield losses, understanding epidemiological studies and evaluation of treatment.

Introduction

Plant diseases which stem from abnormal plant functions or structural changes affect agricultural systems by decreasing yield and product quality. The economic losses caused by plant diseases annually are enormous, estimated at about $220 billion, emphasizing the need for better identification strategies and scoring scales for timely diagnosis and management. (Albattah *et al.*, 2022). Precise and timely identification of plant diseases and assessment of disease severity is crucial for implementing appropriate control measures, minimizing crop losses, and preventing the further spread of pathogens.

Disease quantification serves multiple critical purposes in plant pathology. Standardized disease assessment methods facilitate comparison of results across different studies, locations, and time periods, thereby contributing to a more comprehensive understanding of plant-pathogen interactions and epidemiology (Bock *et al.*, 2010). The quantification of plant diseases requires systematic assessment approaches that can accurately capture the extent and intensity of disease occurrence.

Understanding Plant Diseases

Julius Kuhn, in 1858, defined plant disease as abnormal changes in the physiological processes which disturb the normal activity of plant organs. According to American Phytopathological Society, disease is a deviation from normal functioning of physiological processes of sufficient duration or intensity to cause disturbance or variation or intensity to cause disturbance or cessation of vital activities. From a modern molecular perspective, plant disease can be defined as 'a dynamic interaction between plant host and pathogen, mediated by molecular signaling pathways, where the pathogen successfully overcomes plant defense mechanisms, leading to altered gene expression, cellular dysfunction, and symptom development (Dangl and Jones, 2001).

The Disease Triangle: Factors Influencing Disease Development

The development and severity of plant diseases are influenced by the interaction of three basic factors, *viz.,* a virulent pathogen, a host plant and the environment. Knowledge of these factors is important for the interpretation of disease assessment results.

- **Virulent pathogen:** The pathogenicity genes code for proteins that help in attachment to the host, penetration, cell wall degradation, toxin production that facilitate tissue invasion, suppress host defenses, and promote disease development. The pathogenicity genes also produce defense inhibiting proteins that inhibit

ISSN: 3049-2289

the defense reactions of the host, including the detoxification of phytoalexins.

- **Host plant:** The host plant must be susceptible to the pathogen. Levels of resistance can affect disease development. The resistance may be non-specific, in which, the plant is resistant to all the races of the pathogen, or specific resistance, where resistance is limited to a specific resistance (race specific), a particular host (host specific), or both (race cultivar specific), also known as gene for gene resistance.

- **The Environment:**
  - ➢ Temperature: Every pathogen has specific optimal, minimum, and maximum temperatures for infection and colonization. For example, *Fusarium* is found in warmer regions and *Verticillium* is confined to cooler regions.
  - ➢ Moisture: Free water or high relative humidity is required by many pathogens. Fungal spore germination and bacterial growth require leaf wetness. The duration of leaf wetness is directly related to infection efficiency for many foliar diseases.
  - ➢ Light: Light intensity and duration influence both host susceptibility and pathogen growth. Some pathogens produce spores under specific light conditions, while host defence responses may be light-regulated.
  - ➢ Soil factors: Soil pH, texture, organic matter content, and water-holding capacity affect soilborne diseases. Wind: Wind currents promote spore dispersal, which influences disease spread and secondary infection cycles. On the other hand, wind may shorten leaf wetness duration, which could limit infection.

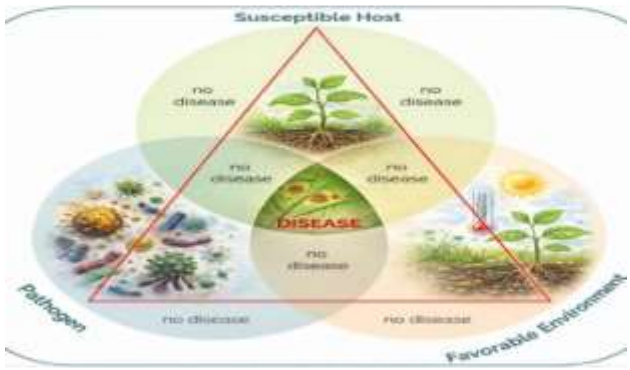


Figure 1: Disease triangle

The Disease Tetrahedron: Adding Time

Modern plant pathologists tend to extend the disease triangle to the disease tetrahedron by incorporating time as the fourth component. The inclusion of time acknowledges the fact that:

- ➢ Disease progression is a process that takes time for pathogen establishment, colonization, and manifestation.
- ➢ The duration of the critical infection period may be restricted to certain growth stages of the crop or seasons.
- ➢ Several infection cycles (polycyclic diseases) require a long favourable period, while monocyclic diseases involve a single infection event per crop season.
- ➢ The timing of infection in relation to crop growth stages affects yield loss.

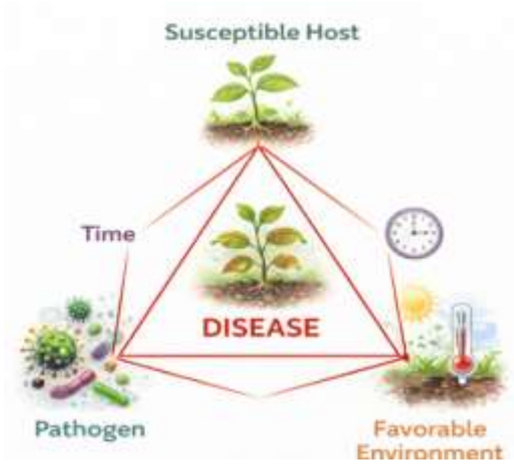


Figure 2: Disease tetrahedron

ISSN: 3049-2289

Disease Quantification Parameters

Disease Incidence

Disease incidence is the proportion or percentage of diseased plants or plant units in a given population. It is a binary index that depends on the presence or absence of disease symptoms, irrespective of the level of infection (Campbell and Madden, 1990). Disease incidence is most appropriate for diseases in which early detection and disease spread are more important than the level of infection. The ease of incidence measurement makes it less prone to observer bias than that of severity measurement. But the data from incidence measurement are of little value in estimating the level of disease, as it may not give an accurate estimate of the disease impact on plant health or yield when the severity of disease is highly variable among the diseased individuals.

Disease incidence is typically expressed as:

Disease Incidence (%) = (Number of diseased plants / Total number of plants assessed) × 100

Disease Severity

Disease severity is the measure of the level of disease symptoms, either on plant parts or on the whole plant. Disease severity is the measure of the percentage of plant tissue showing disease symptoms (Bock *et al.*, 2010).

When assessing individual plants or plant parts, the severity of disease is generally expressed as a percentage:

Disease Severity (%) = (Diseased area / Total area assessed) × 100

Percent Disease Index (PDI)

The Percent Disease Index (PDI), also referred to as Disease Severity Index (DSI), is a comprehensive index that combines both the percentage of diseased plants and the level of disease on each plant. PDI is most useful when rating scales are employed to rate the level of disease on various plants. This index is standardized and enables comparison among various studies conducted on disease assessment (McKinney, 1923).

Using categorical scales of severity, the formula for PDI calculation is as follows:

PDI = [Σ (Disease rating × Number of plants in that rating category) / (Total number of plants × Maximum disease rating)] × 100

Disease Assessment Scales

Types of Assessment Scales

Disease assessment scales are standardized methods of disease intensity classification or measurement. The type of scale to be used depends on the nature of the disease, the purpose of assessment, and the level of accuracy required. The main types are:

- **Categorical Scales:** These are ordinal scales that measure disease intensity by classifying it into discrete categories. They are easy to apply and save time but lack accuracy (Horsfall and Barratt, 1945).
- **Continuous Percentage Scales:** These scales enable the rater to estimate the disease intensity to any percentage between 0 and 100%, which is highly accurate. However, they are more difficult to apply and may be less reliable when used by untrained measurers (Nutter and Esker, 2006).
- **Diagrammatic Scales:** These scales are graphical representations of typical disease severities to enable the rater to standardize the assessment. They are more accurate and less subjective (James, 1971).

Scale of Different Diseases for Calculation of Disease Incidence and Disease Severity

Disease evaluation and calculation of Brown spot index:

ISSN: 3049-2289

Brown spot severity on the grains of each panicle per plant is scored using a 0-7 scale, modified from IRRI (1996) as follows:

Table 1: Severity scale of Brown spot

Scale	Observation
0	No disease symptoms
1	Less than 1%
2	From 1.1 to 5%
3	From 5.1 to 10%
4	From 10.1 to 25%
5	From 25.1 to 50%
6	50.1 to 75%
7	More than 75% of the grains surface with disease symptoms

Data for brown spot severity are used to calculate the BSI based on the formula proposed by McKinney (1923) where:

BSI = [Σ (rate of the disease scale × number of grains receiving that rate)/(total number of grains × the highest rate of the disease scale)] × 100.

Disease scoring scale for brown spot of rice can be done as per the method of Shreshta *et al.*, 2017.

Table 2: Scoring scaling of Brown spot

Scale	Affected area
1	No incidence
2	Less than 1%
3	1-3%
4	4-5%
5	11-15%
6	16-25%
7	26-50%
8	51-75%
9	76-100%

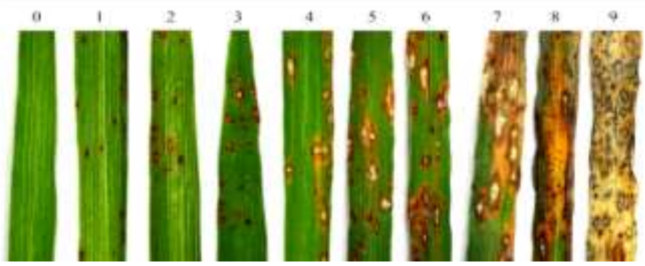


Figure 3: Scoring of infected leaves of Brown spot of rice (Shrestha *et al.*, 2017)

Figure 3: Scoring of infected leaves of Brown spot of rice (Shrestha *et al.*, 2017)
Figure 3: Scoring of infected leaves of Brown spot of rice (Shrestha *et al.*, 2017)
Figure 3: Scoring of infected leaves of Brown spot of rice (Shrestha *et al.*, 2017)
Figure 3: Scoring of infected leaves of Brown spot of rice (Shrestha *et al.*, 2017)
Figure 3: Scoring of infected leaves of Brown spot of rice (Shrestha *et al.*, 2017)
Figure 3: Scoring of infected leaves of Brown spot of rice (Shrestha *et al.*, 2017)
Figure 3: Scoring of infected leaves of Brown spot of rice (Shrestha *et al.*, 2017)
Figure 3: Scoring of infected leaves of Brown spot of rice (Shrestha *et al.*, 2017)
Figure 3: Scoring of infected leaves of Brown spot of rice (Shrestha *et al.*, 2017)

ISSN: 3049-2289

	infecting less than 4% of leaf area.	
5	Typical susceptible blast lesions, infecting 4-10% of leaf area.	**Moderately Resistant**
6	Typical susceptible blast lesions, infecting 11-25% of leaf area.	**Susceptible**
7	Typical susceptible leaf blast lesions infecting 26-50% of the leaf area.	**Susceptible**
8	Typical susceptible leaf blast lesions infecting 51-75% of the leaf area, and many dead leaves as well.	**Susceptible**
9	More than 75% leaf area affected.	**Susceptible**

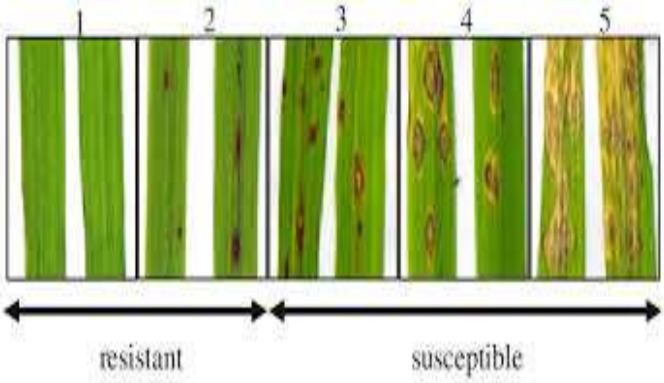


Figure 3: Infection scale of Blast of rice

Quantitative assessment for Fusarium wilt of Banana disease

Disease development of Fusarium wilt of Banana can be monitored based on quantitative assessment of foliar associated symptoms at intervals of 8 days and expressed as percentage disease severity (DS%) using a scale of 0 to 4.

Table 6: Infection scoring scale for Fusarium wilt of banana

Rating	Leaf Area Affected (%)	Description
0	0	No symptoms; apparently healthy leaves
1	<1	<1% of leaf area affected by disease
2	1-5	1-5% of leaf area affected by disease
3	6-15	6-15% of leaf area affected by disease
4	16-33	16-33% of leaf area affected by disease
5	34-50	34-50% of leaf area affected by disease
6	>51	>51% of leaf area affected by disease

Disease severity (%) for both external and internal symptoms of Fusarium wilt can be calculated based on the following formula:

$$DS(\%) = \frac{\sum(\text{No of diseased plantlets in each rating category} \times \text{Severity Rating})}{(\text{Total number of plantlet assessed} \times \text{Highest Scale})} \times 100\%$$

A reduction in the DS compared with control would be a measure of the treatment effectiveness in suppressing Fusarium wilt disease. This was assessed by plotting the data as disease progress curves calculated using the formula (Campbell and Madden 1990).

$$AUDPC = \sum_{i}^{n-1} [Y_i + Y_{i+1}/2]\,[t_{i+1} - t_i]$$

Where, Y = disease incidence, t=weeks, and n=number of assessment times.

The slopes of the curves can be obtained by transforming the DS data using the monomolecular model (Monit) (Campbell and Madden 1990).

Disease scoring of leaf spot of turmeric caused by *Colletotrichum capsici*

The disease scale for measuring the disease severity of leaf spot of turmeric can be done using the 0-6 scale as proposed by Palarpawar and Ghurde (1989).

Table 8: Disease rating scale of leaf spot of turmeric

Rating	Severity observation
0	No infection.
1	0.1 to 10% leaf area infected.
2	10.1 to 20% leaf area infected.
3	20.1 to 30% leaf area infected.
4	30.1 to 40% leaf area infected.
5	40.1 to 50% leaf area infected.
6	More than 50% leaf area infected.

Root knot index to score the infestation of *Meloidogyne incognita*

The infestation of *M. incognita* is scored using the scale developed by Arnon, 1993, which is given below:

Table 9: Scale for scoring infestation caused by *M. incognita*

Number of galls	Scale (based on number of root-knot galls/root)	Reaction
0	1	HR (Highly Resistant)
1-10	2	R (Resistant)
11-30	3	MR (Moderately Resistant)
31-100	4	S (Susceptible)
101 and above	5	HS (Highly Susceptible)

Lesion index scale (0-4 scale) for burrowing nematode, *Radopholus similis*

The lesion index for burrowing nematode was proposed by Ravichandra and Krishnappa in 1985 and is mentioned below.

Table 10: Lesion index scale for *R. similis*

Scale	Description
0	No lesion
1	Few up to 1 mm diameter (1-20 lesions)
2	Many up to 1 mm diameter (21-50 lesions)
3	Many up to 1 mm diameter (51-100 lesions)
4	Very severe 1 cm diameter (>100 lesions)

Conclusion

Precision in disease estimation is still the essence of plant pathology and crop protection. The variety of disease estimation techniques, ranging from simple incidence estimation to complex image analysis, indicates the complexity of plant-pathogen interactions and the diverse goals of disease estimation. Continuous percentage estimation has greater precision and statistical power and is, therefore, more suitable for research work where small differences between treatments need to be detected. Rating scales have advantages in terms of efficiency and consistency and are, therefore, more suitable for large-scale disease estimation and rapid assessment of numerous samples.

References

Albattah, W., Javed, A., Nawaz, M., Masood, M., and Albahli, S. (2022). Artificial intelligence-based drone system for multiclass plant disease detection using an improved efficient convolutional neural network. *Front. Plant Sci.*, 13, 808380.

ISSN: 3049-2289

Bock, C. H., Poole, G. H., Parker, P. E., and Gottwald, T. R. (2010). Plant disease severity estimated visually, by digital photography and image analysis, and by hyperspectral imaging. *Crit. Rev. Plant Sci.*, **29**(2), 59-107.

Campbell C L, Madden L V. (1990). *Introduction to Plant Disease Epidemiology*. John Wiley and Sons, New York. p. 532.

Dangl, J. L., and Jones, J. D. G. (2001). Plant pathogens and integrated defence responses to infection. *Nature*, 411(6839), 826-833.

Dutta Pranab (2021) Manual on diagnosis and detection of plant diseases. Eds. Dutta, P, Publ by Biotica publishers, Tripura, ISBN: 978-81-947739-6-2.

Horsfall, J.G., and Barratt, R.W. (1945). An improved grading system for measuring plant diseases. *Phytopathology*, 35, 655.

IRRI (1996). Standard evaluation system for rice. Los Banos Philippines. International Rice Research Institute.

James, W.C. (1971). An illustrated series of assessment keys for plant diseases, their preparation and usage. *Can. Plant Dis. Surv.*, 51, 39-65.

McKinney, H.H. (1923). Influence of soil temperature and moisture on infection of wheat seedlings by *Helminthosporium sativum*. *J. Agric. Res.,* 26:195-218.

Nutter, F.W., and Esker, P.D. (2006). The role of psychophysics in phytopathology: The Weber-Fechner law revisited. *Eur. J. Plant Pathol.*, 114(2), 199-213.

Palarpawar, M. Y. and Ghurde, V.R. (1989). Fungicidal control of leaf spot of turmeric incited by Colletotrichumcurcumae. *Indian Phytopathol.*, 42: 576-578

Ravichandra NG, Krishnappa K (1985). Effect of various pesticides on the control of the burrowing nematode, Radopholus similis infecting banana. *Indian J Nematol*. 15:26-29

Shrestha, S., Aryal, L., Parajuli, B., Panthi, J., Sharma, P., and Saud, Y. S. (2017). Field Experiment to Evaluate the Efficacy of Different Doses of Chemical Fungicides against Rice Brown Leaf Spot Disease Caused by *Bipolaris oryzae* L. at Paklihawa, Rupandehi, Nepal. *World J. Agric. Res.*, **5**(3), 162-168.

ISSN: 3049-2289

Role of Extension Education in Dissemination of System of Millet Intensification Technology

Dravin Maurya*, Vivek Yadav and Shivam Maurya*****

*M.Sc. scholar, Department of Agricultural Extension, Banda University of Agriculture and Technology, Banda

**M.Sc. scholar, Department of Soil Science, B.M. Memorial P.G. College, Ambedkar Nagar

***M.Sc. scholar, Department of Horticulture, Tilak Dhari Post Graduate College, Jaunpur

Millets are widely acknowledged as climate-resilient crops that are rich in nutrients and possess considerable potential to strengthen food and nutritional security, particularly within rainfed and marginal agricultural systems. The System of Millet Intensification (SMI), which draws inspiration from the System of Rice Intensification (SRI), has recently gained attention as an improved crop management approach aimed at increasing millet productivity and improving efficiency in the use of available resources. Despite these advantages, the adoption of SMI is still uneven and relatively limited in many regions. This paper presents a theoretical and review-oriented examination of SMI adoption from the viewpoint of agricultural extension education. Through a synthesis of available literature, the study discusses the conceptual basis of SMI, relevant theoretical frameworks of technology adoption, the role played by extension services, and the major constraints influencing farmers' adoption behaviour. The review highlights the need for effective extension approaches, capacity-building initiatives, and enabling policy support to encourage broader adoption of SMI among millet-growing farmers.

Introduction

Millets are among the oldest cultivated crops in India and play a significant role in supporting food security, nutrition, and rural livelihoods, particularly in arid and semi-arid regions. These crops are well adapted to low-input agricultural systems, show strong tolerance to drought conditions, and can grow successfully in soils with poor fertility, making them highly suitable for small and marginal farmers. With increasing concerns about climate change, rising agricultural input costs, and the need for sustainable farming practices, millets are now increasingly recognized as climate-smart crops that can contribute to building more resilient agricultural systems. Nevertheless, millet productivity in India remains comparatively low due to the continued use of traditional cultivation practices, inadequate access to improved technologies, and limited extension services. To address these challenges, innovative crop management practices such as the System of Millet Intensification (SMI) have been introduced in several millet-producing regions. However, farmers' adoption of SMI has not yet reached the level expected considering its potential benefits. Therefore, gaining a clear understanding of the SMI adoption process through theoretical perspectives and the framework of extension education is essential.

Importance of Millets in Indian Agriculture

Millets play an important role in strengthening nutritional security because they contain high levels of dietary fibre, essential micronutrients, and minerals. They are particularly significant in rainfed and tribal regions where farmers often face resource constraints that limit the cultivation of high-input crops. Moreover, millets generally require less water and fewer chemical inputs compared with major cereals, which helps reduce production risks as well as environmental damage. Although India is among the leading producers of millets globally, noticeable productivity gaps continue to exist due to weak market linkages and the limited adoption of improved agronomic practices. These challenges underline the importance of promoting efficient production technologies along with stronger marketing and distribution systems.

Concept and Principles of System of Millet Intensification

The System of Millet Intensification (SMI) is an agronomic approach derived from the principles of the System of Rice Intensification (SRI). This method focuses on practices such as using healthy seedlings, maintaining wider plant spacing, reducing seed rates, carrying out timely intercultural operations, and applying improved soil and water management techniques to promote better crop growth and productivity. Evidence from research studies and field experiences indicates that SMI practices can improve tiller formation, root development, and nutrient-use efficiency in millet crops, ultimately leading to higher yields while lowering input costs. However, the successful adoption of SMI depends largely on effective knowledge transfer and behavioural change among farmers, since it requires adjustments in traditional cultivation practices.

Theoretical Perspectives and Role of Extension in Technology Adoption

The adoption of agricultural innovations is essentially a behavioural process influenced by socioeconomic, psychological, and institutional factors. Rogers' Diffusion of Innovations theory explains adoption as a gradual process involving stages such as knowledge, persuasion, decision, implementation, and confirmation. According to this framework, farmers' awareness and perceptions regarding the benefits of SMI play a crucial role in shaping their adoption decisions. Extension approaches such as farmer field schools, on-farm demonstrations, and capacity-building programmes help farmers understand the practical benefits of new agricultural technologies. Furthermore, well-functioning extension systems act as a bridge between research organizations and farming communities by ensuring that locally relevant information and recommendations are effectively communicated. Strengthening participatory learning methods and enhancing the technical capacity of extension personnel in SMI can significantly improve adoption outcomes. In this context, agricultural extension education becomes essential in enhancing farmers' knowledge, skills, and confidence to implement improved practices. Extension activities such as training programmes, demonstrations, and farmer-to-farmer learning have been shown to positively influence adoption behaviour.

Adoption of SMI: Evidence from Existing Literature

Empirical studies on millet cultivation indicate that awareness and adoption of improved millet production practices remain moderate to low in many regions. Bhakar et al. (2024) reported that farmers' adoption of improved millet production technologies was significantly constrained by limited technical knowledge and inadequate contact with extension services. In a similar context, researchers have identified considerable gaps in farmers' understanding of recommended millet cultivation practices. Although specific adoption studies focusing exclusively on SMI are relatively limited, the available literature suggests that factors such as labour requirements, availability of suitable implements, and farmers' perception of risk influence their willingness to adopt intensive crop management practices. These findings highlight the critical role of extension support in addressing farmers' concerns and reducing the perceived complexity associated with SMI practices.

Policy and Institutional Perspectives

Government initiatives promoting millets, including mission-mode programmes and policy incentives, have created favourable opportunities for expanding millet-based innovations. Policy support in the form of training programmes, input subsidies, and improved market linkages can strengthen farmers' confidence in adopting practices such as SMI. In addition, effective institutional coordination among research organizations, extension agencies, and development programmes is essential to ensure consistent communication and continuous support for the adoption of SMI technologies.

Conclusion

The System of Millet Intensification holds considerable promise for improving both productivity and sustainability of millet cultivation in rainfed farming systems. However, its adoption depends not only on technical feasibility but also on strong institutional support, enabling policy environments, and effective extension education. This review emphasizes the importance of targeted extension strategies, continuous capacity-building efforts, and the adaptation of SMI practices to local conditions. Future efforts should focus on strengthening linkages between research and extension systems and documenting farmers' experiences to facilitate the wider dissemination of SMI practices.

References

1. **Pretty, J., Toulmin, C. and Williams, S. (2011).** Sustainable intensification in African agriculture. *International Journal of Agricultural Sustainability*, **9** (1): 5–24.
2. **Prasad, C. S. and Ravi, S. B. (2013).** Millets for food security and climate resilience. *Indian Journal of Agricultural Research*, **47** (6): 469–476.

AGRICULTURE BULLETIN
ISSN: 3049-2289

Biotechnological Approaches against Root-Knot Nematodes in Brinjal for Sustainable Farming

Deepak Kumar Bhankhar, Hari Singh Meena and Kapil Dev Poonia
Rajasthan College of Agriculture,
MPUAT, Udaipur (313001)- Rajasthan

The biotechnological approaches to combat root-knot nematodes, particularly in brinjal (*Solanum melongena* L.), a vital vegetable crop susceptible to significant yield losses due to these pests. Root-knot nematodes, mainly *Meloidogyne incognita* and *Meloidogyne javanica*, disrupt root function, resulting in stunted growth and reduced fruit yield. Traditional reliance on chemical nematicides poses environmental and economic challenges, thus, this article advocates for sustainable and eco-friendly alternatives. Key biotechnological strategies discussed include the utilization of nematode-resistant brinjal varieties, beneficial fungi and bacteria as bio-control agents, RNA interference technology and various bioproducts derived from natural sources. These methods not only enhance crop resilience and productivity but also promote soil health. It emphasizes the integration of the various biotechnological practices with sound agricultural methods for effective nematode management and aiming to ensure long-term sustainable brinjal farming. Future advancements in biotechnology may further enhance these strategies, offering promising solutions for nematode control.

Introduction

Brinjal (*Solanum melongena* L.), commonly called eggplant, is one of the most widely grown vegetable crops in India and many tropical countries. It is valued for its high nutritional content, adaptability to different climatic conditions and continuous fruit production. However, brinjal cultivation is frequently affected by several pests and diseases, among which root-knot nematodes are one of the most damaging soil-borne pests. Root-knot nematodes mainly belong to the genus *Meloidogyne* and dominant species are *Meloidogyne incognita* and *Meloidogyne javanica*. These microscopic worms infect the roots of plants and form galls or knots, which disturb the normal uptake of water and nutrients. As a result, plants show symptoms such as stunted growth, yellowing of leaves, poor flowering and low fruit yield. In severe infestations, yield losses may reach 30-60%.

Traditionally, farmers have relied on chemical nematicides to control nematodes. However, these chemicals are expensive, harmful to beneficial soil organisms and may cause environmental pollution. Therefore, biotechnological approaches provide safer, eco-friendly and sustainable methods for managing root-knot nematodes in brinjal fields.

Root-Knot Nematode Damage: The nematodes live in the soil and attack plant roots. The second-stage juvenile (J2) enters the roots and establishes feeding sites known as '*giant cells*'. These cells supply nutrients to the nematode and cause the formation of root galls.

Brinjal root heavily infested with *Meloidogyne incognita*

Microscopic view of heavily infested Brinjal root with *Meloidogyne incognita*

Symptoms produced in Brinjal: Farmers may notice the following symptoms in affected fields-

- Swollen galls or knots on roots
- Yellowing of leaves

- Stunted plant growth
- Wilting even with adequate irrigation (generally day wilting)
- Reduced fruit size and yield

If infected roots are uprooted and examined, they appear distorted and swollen which is a typical sign of nematode infestation.

Importance of Biotechnological Approaches

Biotechnology uses beneficial microorganisms, plant genetics and molecular tools to improve crop protection. These approaches help farmers manage nematodes effectively while maintaining soil health. These approaches help the farmers for reduced use of chemical nematicides, eco-friendly management, improved soil fertility and microbial activity, long-term effect and finally increased crop productivity.

Major Biotechnological Approaches for Nematode Management

1. **Use of Nematode-Resistant Brinjal Varieties:** One of the most effective methods to control root-knot nematodes is the use of resistant or tolerant brinjal varieties. Farmers are encouraged to select nematode-tolerant hybrids recommended by agricultural universities or extension agencies.
2. **Use of Beneficial Fungi (Bio-Control Agents):** Certain beneficial fungi naturally attack nematodes and reduce their population in the soil. Mechanism of these fungi against nematodes includes parasitize nematode eggs, destroy juvenile nematodes, improve plant root growth and increase plant resistance.

Important Fungal Bio-Agents: *Trichoderma viride, T. harzianum, Purpureocillium lilacinum* (formerly *Paecilomyces lilacinus*), *Pochonia chlamydosporia* etc.

Method of Application: Farmers can apply fungal bio-agents through seed treatment, soil application with farmyard manure, root dipping before transplanting etc.

Example: Mix 2-5 kg of *Trichoderma* formulation with 100 kg FYM and apply it to the field before transplanting brinjal seedlings.

3. **Use of Plant Growth-Promoting Rhizobacteria (PGPR):** Certain beneficial bacteria live around plant roots and help control nematodes while improving plant growth.

Important Bacterial Bio-Agents: *Pseudomonas fluorescens, Bacillus subtilis, Azotobacter chroococcum, Azospirillum brasilense* etc.

Mechanism of these bacteria against nematodes:

- Produce substances toxic to nematodes
- Stimulate plant immune responses
- Promote root development
- Improve nutrient uptake

Method of Application: Seed treatment with bacterial culture, Root dipping of seedlings and soil application mixed with organic manure.

4. **RNA Interference (RNAi) Technology:** RNA interference is an advanced biotechnology technique that can block important genes in nematodes, preventing them from growing or reproducing. Scientists develop plants capable of producing specific molecules that silence nematode genes, reducing their ability to infect plant roots. Although still under research in many crops, RNAi technology shows great promise for future nematode-resistant brinjal varieties.
5. **Induced Systemic Resistance (ISR):** Certain beneficial microorganisms stimulate natural defense mechanisms in plants. This

process is called Induced Systemic Resistance. Bio-agents such as *Trichoderma* and *Pseudomonas* are known to trigger ISR in vegetable crops. Plants produce defensive enzymes, root tissues become stronger and nematodes fail to establish feeding sites.

6. **Use of Biotechnological Bio-Products:** Several eco-friendly bio-products derived from natural sources help manage nematodes. Many commercial bio-nematicides are now available for farmer use.

Examples include:

- **Chitosan-based formulations:** Chitosan oligosaccharide (COS) formulations, Nano-chitosan formulations, Chitosan nanoparticles, Chitosan-based nanocomposites, Sulfonamide-modified chitosan oligosaccharides
- **Microbial metabolites:**

❖ **From Bacteria:**

✓ Avermectins - produced by *Streptomyces avermitilis*

✓ 2,4-diacetylphloroglucinol (DAPG) - produced by *Pseudomonas fluorescens*

✓ Hydrogen cyanide (HCN) - produced by *Pseudomonas* spp.

✓ Bacillomycin and surfactin - produced by *Bacillus subtilis*

❖ **From Fungi:**

✓ Paecilotoxin - from *Purpureocillium lilacinum*

✓ Destruxins - from *Metarhizium anisopliae*

✓ Trichodermin and gliotoxin - from *Trichoderma* species

- **Enzyme inhibitors:**

❖ **Plant-Derived Proteinase Inhibitors:** Soybean trypsin inhibitor, Cowpea trypsin inhibitor, Potato proteinase inhibitors etc.

❖ **Other Enzyme-Targeting Compounds:** Chitinase inhibitors, Acetylcholinesterase inhibitors, Protease inhibitors etc.

- **Botanical extracts:**

❖ Neem (*Azadirachta indica*): Azadirachtin- Reduces egg hatching and juvenile survival

❖ Garlic (*Allium sativum*): Allicin- Toxic to nematodes

❖ Marigold (*Tagetes* spp.): Thiophenes- Suppresses Meloidogyne species

❖ Castor (*Ricinus communis*): Ricin and fatty acids- Nematicidal activity

❖ Mustard (*Brassica* spp.): Glucosinolates- Produce toxic isothiocyanates

❖ Papaya (*Carica papaya*) leaves: Papain enzyme- Nematode suppression

Mechanism of these substances against nematodes: Reduce nematode egg hatching, Inhibit juvenile development and Improve plant immunity.

Integrated nematode management practices for better effectivity: For effective control, farmers should combine biotechnological methods with good agricultural practices. These may be use nematode-free seedlings, application of *Trichoderma* or *Pseudomonas* in nursery beds, mixing of bio-agents with organic manure, practice crop rotation, maintaining proper soil fertility and avoid continuous monocropping of brinjal etc.

Conclusion

Root-knot nematodes pose a serious challenge to brinjal cultivation leading to significant yield losses if not properly managed. Biotechnological approaches including resistant varieties, microbial bio-agents, plant growth-promoting bacteria, RNA

ISSN: 3049-2289

interference technology and bio-based products, offer safe and sustainable solutions for controlling these pests. By adopting these eco-friendly practices, farmers can effectively manage nematode problems, improve soil health and ensure profitable and sustainable brinjal production.

Future Prospects

Recent advances in biotechnology such as genome editing, molecular breeding and improved microbial bio-formulations are expected to provide even more effective solutions for nematode management.

ISSN: 3049-2289

Smart Nano-Packaging for Real-Time Food Quality Monitoring

Vivek Yadav*, Shivam Maurya and Dravin Maurya*****

* M.Sc. Scholar, Department of Soil Science, B.M. Memorial P.G. College, Ambedkar Nagar

** M.Sc. Scholar, Department of Horticulture, Tilak Dhari Post Graduate College, Jaunpur

*** M.Sc. Scholar, Department of Agricultural Extension, Banda University of Agriculture and Technology, Banda

A quiet yet profound transformation is emerging within the field of food packaging, driven not by distant futuristic inventions but by materials engineered at scales invisible to the naked eye. Amid rising global demands for food that is safer, fresher and environmentally responsible, researchers are increasingly applying nanotechnology to redesign the microscopic structures that enclose everyday products. Nano-enabled packaging, positioned between materials science and food engineering is reshaping methods of preservation, surveillance and distribution across the supply network. By tailoring matter at the nanoscale level, scientists develop films with greater strength, improved functionality and responsive characteristics beyond conventional plastics. These advanced systems can suppress microbial growth, limit the penetration of oxygen and moisture and even signal the onset of spoilage. Thus, packaging is no longer merely a passive container but is becoming an active guardian of food quality, integrity and consumer safety worldwide today, ensuring longer shelf life and reduced waste throughout complex global distribution channels and retail environments alike for modern food systems everywhere.

The Technology Behind Nano-Packaging

Nano-packaging is founded on the principles of nanotechnology, which involves the study and manipulation of matter at the atomic and molecular scale, typically ranging from 1 to 100 nanometers. For comparison, a single strand of human hair measures approximately 80,000 nanometers in diameter. Working at such an extremely small scale allows scientists to engineer packaging materials with exceptional characteristics, making them stronger, lighter and significantly more functional than traditional alternatives. To improve the performance of packaging substances such as plastics, biopolymers or surface coatings, nanoparticles are incorporated to strengthen barrier efficiency, enhance antimicrobial activity and extend product shelf life. These nano-enhanced materials can actively interact with food and its surrounding environment, contributing to the development of advanced “smart” and active packaging technologies.

Active Packaging: Extending Freshness and Protection

Conventional packaging primarily serves as a protective covering for food products. In contrast, active nano-packaging plays a dynamic role by interacting with both the food and the surrounding environment to preserve quality. Antimicrobial surfaces are developed through the incorporation of nanoparticles such as silver, zinc oxide, titanium dioxide and chitosan-based nanocomposites, which inhibit bacterial growth on contact surfaces. For instance, silver nanoparticles release ions that interfere with microbial cell membranes, leading to the destruction of bacteria and fungi. In addition to eliminating microorganisms, zinc oxide and titanium dioxide nanoparticles shield food from light-induced spoilage by absorbing or blocking harmful ultraviolet radiation. Nanoclays further enhance packaging performance by strengthening barrier properties and minimizing the transmission of oxygen and moisture, two major contributors to food degradation.

ISSN: 3049-2289

Smart Packaging: Intelligent Monitoring Systems

Smart nano-packaging goes beyond basic protection by continuously observing the condition of food products. Embedded nanosensors are extremely small yet capable of detecting variations in pH levels, temperature fluctuations and gas concentrations, thereby indicating whether the product remains safe for consumption. For example, certain packaging systems are engineered to change color when spoilage begins, providing a clear visual warning to consumers. Sensors based on gold nanoparticles, carbon nanotubes or quantum dots can deliver real-time data regarding freshness, contamination or even trace amounts of pesticide residues. Such technological advancements enable retailers and consumers to make informed decisions, ultimately reducing food waste while improving overall safety standards.

Sustainable Innovations in Biodegradable Nano-Materials

One of the most promising dimensions of nano-packaging lies in its potential to advance environmental sustainability. Scientists are actively designing biodegradable packaging solutions derived from renewable polymers such as starch, cellulose, polylactic acid (PLA) and chitosan. The incorporation of nanoparticles, including nanoclay and nano-silica, reinforces these bio-based materials, enhancing their mechanical strength, flexibility and barrier performance. As a result, they can achieve functionality comparable to conventional plastics while significantly reducing ecological impact. Such developments respond to the growing global demand for environmentally responsible packaging and support the principles of a circular economy. In the near future, food wrappers may not only preserve freshness effectively but also decompose safely after disposal, returning harmlessly to the natural environment.

Applications Already Creating Industry Impact

The commercial food sector has already begun integrating nano-packaging technologies in several practical applications. For example, fresh fruits and vegetables are now treated with nanosilver-based coatings to slow microbial deterioration and extend shelf life. Packaging films used for meat products are infused with zinc oxide (ZnO) nanoparticles to minimize oxidation and delay spoilage. Similarly, dairy and beverage containers incorporate nanoclay particles to enhance gas barrier properties, preventing the entry of oxygen and maintaining product freshness. In addition, smart labeling systems equipped with nanosensors are employed to monitor temperature fluctuations during transportation and storage.

Collectively, these advancements are reshaping quality control throughout the farm-to-fork supply chain, delivering safer food products, prolonged shelf stability and reduced dependence on chemical preservatives.

Challenges and Safety Considerations

Despite its considerable promise, nano-packaging raises important safety and regulatory concerns. Scientists and international authorities-including the FAO, WHO, EFSA, and FSSAI-are carefully evaluating potential risks such as nanoparticle migration from packaging into food, possible contamination and long-term health or environmental effects. Comprehensive toxicological assessments, ecological compatibility studies and transparent communication are essential before large-scale commercialization can occur. Bridging the gap between technological innovation and public acceptance requires clear labeling practices and rigorous risk evaluation to ensure consumer confidence and regulatory compliance.

The Road Ahead

The future of food packaging is expected to become more intelligent, interactive and environmentally

ISSN: 3049-2289

responsible. Nano-packaging stands at the crossroads of scientific innovation and sustainability, offering solutions to major industry challenges such as spoilage, contamination, and excessive waste. As research continues to advance, it is likely that packaging systems will soon not only indicate whether food remains safe for consumption but may also possess the ability to self-repair when damaged or eliminate harmful pathogens upon contact. In essence, nano-packaging is not merely a gradual improvement; it represents a transformative leap in safeguarding both food quality and environmental health.

Conclusion

Nano-packaging signifies a progressive movement toward a future in which food retains freshness for extended periods, supply networks operate with greater efficiency and consumers gain access to real-time product information. By utilizing the distinctive characteristics of nanoparticles, researchers are engineering packaging materials capable of actively protecting food, continuously monitoring its condition and minimizing the ecological impact associated with conventional plastics. Although significant challenges remain-particularly in areas of safety evaluation, regulatory approval and public acceptance-the promise of nano-packaging remains substantial. As technological developments continue, packaging may soon demonstrate self-healing properties, instantly neutralize pathogens or decompose safely after disposal. Ultimately, nano-packaging extends beyond scientific advancement; it represents a transformative strategy aligned with global objectives for food safety, waste reduction and sustainable living.

References

- **Khan, S., Hosseinidoust, Z., Li, Y., Filipe, C. D. M. and Didar, T. F. (2024).** Smart food packaging commercialization. *Nature Reviews Bioengineering.* **2:** 535–537.
- **Kalpana, S., Priyadarshini, S. R. B., Leena, M. M. and Moses, J. A. (2019).** Intelligent packaging: Trends and applications in food systems. *Trends in Food Science and Technology.* **93:** 145–157.
- **Kerry, J. P., O'Grady, M. N. and Hogan, S. A. (2006).** Past, current and potential utilization of active and intelligent packaging systems for meat and muscle-based products: A review. *Meat Science.* **74** (1): 113–130.

AGRICULTURE BULLETIN

ISSN: 3049-2289

Artificial Intelligence as the farmer's new decision companion

Shubha Bisotra (Manager Research)

State Bank Institute of Innovation & Technology, Hyderabad

Will Artificial Intelligence replace farmers, or will it help them farm smarter? This question is increasingly shaping discussions around the future of agriculture as digital technologies enter fields across the world. Farming has always depended on experience, observation, and timely decisions - from choosing the right crop to managing water, pests, and harvest timing. However, modern agriculture faces growing uncertainty due to changing climate patterns, fluctuating markets, and rising input costs. In this environment, Artificial Intelligence (AI) is emerging not as a substitute to traditional methods, but as a decision-support system that helps them interpret complex information and act with greater confidence. By analysing data from weather forecasts, soil conditions, crop health, and market trends, AI provides recommendations that support better planning and risk reduction. The farmer remains at the center of the process, while AI functions as an intelligent partner that strengthens decision-making in everyday farming operations.

(I) Changing nature of farming decisions

Modern agriculture is increasingly influenced by unpredictable weather, market fluctuations, and rising input costs. Farmers must make multiple decisions related to crop selection, irrigation, and pest management under uncertain conditions. As farming becomes more complex, the need for data-supported decision-making is growing rapidly.

1. Climate variability and weather uncertainty

One of the biggest challenges facing farmers is the increasing unpredictability of weather patterns. Irregular rainfall, unexpected dry spells, heat waves, and unseasonal storms can significantly affect crop growth and yield. Traditional seasonal patterns that farmers once relied upon are becoming less predictable, making it difficult to decide the right sowing time or irrigation schedule. Even a small change in weather conditions can lead to substantial losses, particularly for small and marginal farmers.

In 2025, AI-based monsoon forecasts distributed by the Indian Ministry of Agriculture in collaboration with University of Chicago Institute for Climate & Sustainable growth reached about 3.8 crore farmers, providing predictions up to 30 days in advance.

Source: World Economic Forum Insight Report August 2025: Future Farming in India

These forecasts accurately anticipated an unusual monsoon pattern, helping farmers make better planting and crop decisions before the rains arrived. This demonstrates how AI-driven weather intelligence can reduce climate-related uncertainty and support climate-resilient farming decisions.

2. Rising Input Costs and Resource Management

The cost of essential agricultural inputs such as seeds, fertilizers, pesticides, fuel, and labour continues to rise. Farmers must carefully balance productivity with affordability, deciding how much input to apply without increasing financial risk. Overuse of fertilizers or water not only raises costs but can also reduce soil health and long-term sustainability. Efficient decision-making has therefore become

ISSN: 3049-2289

essential to maintain profitability while conserving resources.

Several AI-supported precision agriculture projects are already focusing on reducing input costs through data-driven recommendations. For example, an AI-based precision farming pilot in Jharkhand by Centre for Development of Advanced Computing (CDAC), uses satellite imagery, weather data, and soil information to provide farmers with tailored irrigation and fertilizer advisories through digital platforms. Similar precision nutrient management initiatives have demonstrated yield improvements of 6–15% and nitrogen savings of 5–25 kg per hectare, showing how AI can help farmers optimise input use while maintaining productivity. These initiatives highlight how data-driven decision support can reduce costs and improve sustainability in modern agriculture.

3. Pest and Disease Pressure

Changing climate conditions and intensive farming practices have increased the frequency of pest and disease outbreaks. Farmers often face difficulty identifying early signs of crop stress or disease, which leads to delayed action and higher losses. In many cases, decisions regarding pesticide application are based on visual observation rather than early detection, resulting in either excessive use or insufficient protection.

AI-supported pest monitoring projects are already being used to improve early detection and reduce crop losses. For example, Wadhwani AI's agriculture initiatives in India use image-based analysis and digital monitoring tools to help identify pest outbreaks earlier, addressing a major challenge where manual detection is often delayed. Studies indicate that pests and diseases can cause 20–40% annual crop losses, highlighting the importance of early warning systems and data-driven intervention. By enabling timely identification and targeted pesticide use, AI-based pest surveillance supports more efficient and sustainable crop protection.

4. Market Uncertainty and Price Volatility

Even when crop production is successful, farmers face uncertainty in market prices. Sudden price drops, changing demand, and lack of timely market information make it difficult to decide the best time to sell produce. As a result, many farmers are forced to sell under unfavorable conditions, reducing income despite good yields.

Several initiatives are working to address these challenges through technology-driven solutions. DeHaat, a full-stack agritech platform, integrates AI-based crop advisory with input supply and market linkage services for farmers. By providing digital recommendations on crop planning, pest management, and farm operations, the platform helps reduce uncertainty in decision-making. It is estimated to support nearly 18 lac farmers across multiple states in India.

5. Information Overload and Decision Complexity

Modern farming requires managing information from multiple sources including weather forecasts, market trends, soil health data, and crop management practices. Processing all this information and translating it into practical decisions can be challenging, especially for farmers with limited access to advisory services. This increasing complexity highlights the need for tools that can simplify data and support decision-making at the farm level.

AI-based digital advisory platforms are helping farmers manage complex information by combining multiple data sources into simple recommendations. For example, platforms such as Cropin (an Indian Agritech company) integrate weather forecasts, satellite imagery, soil data, and field observations to generate clear guidance on crop health, irrigation, and farm operations. Instead of analysing separate sources independently, farmers receive actionable

ISSN: 3049-2289

insights in a simplified format, helping them make faster and more informed decisions at the farm level.

(II) AI as a decision support system in agriculture

Artificial Intelligence helps farmers convert complex agricultural data into simple, actionable recommendations. By analysing information from weather forecasts, soil conditions, crop health, and market trends, AI supports better planning and reduces uncertainty. Instead of replacing traditional knowledge, AI strengthens farmers' ability to make timely and informed decisions.

1. Crop Planning and Selection

Choosing the right crop is one of the most important farming decisions, influenced by soil suitability, climate, and market demand. AI systems can analyse historical weather patterns and soil data to suggest crops that are more likely to perform well under specific conditions. This helps farmers reduce risk and improve yield stability.

2. Irrigation and Water Management

Water availability is becoming a critical challenge in agriculture, making efficient irrigation decisions essential. AI tools combined with soil moisture sensors and weather forecasts help farmers decide when and how much water to apply. This improves water efficiency, reduces wastage, and supports sustainable farming practices.Smart irrigation systems supported by AI have shown potential to reduce water use by 20–30% while maintaining crop productivity in several pilot projects.

3. Pest and Disease Early Warning

AI-based monitoring systems can identify early signs of crop stress and disease through image analysis and data patterns. Early detection enables farmers to take preventive action rather than responding after damage occurs. This reduces crop losses and supports more targeted use of pesticides.

4. Fertilizer and Input Optimization

Applying the right quantity of fertilizer at the right time is crucial for both productivity and soil health. AI helps analyse crop requirements and soil conditions to recommend optimal input usage. This reduces unnecessary expenses while improving long-term soil sustainability.

5. Market Intelligence and Selling Decisions

AI-supported digital platforms can analyse market trends and price movements to help farmers make better selling decisions. Access to timely market insights reduces uncertainty and allows farmers to plan harvest and sales more strategically. This improves income stability and reduces distress selling.

(III) Data, Digital Platforms and Smart Farming

The growth of digital platforms and mobile-based advisory services is making agricultural intelligence more accessible to farmers. Data collected from satellites, sensors, and weather systems is increasingly used to guide farm-level decisions. This shift toward data-driven agriculture helps farmers move from guesswork to informed planning.

1. Mobile-based advisory services

Smartphones have become an important channel for delivering agricultural advice to farmers. AI-powered advisory platforms provide recommendations related to crop care, irrigation, and weather risks. These services help bridge knowledge gaps, especially for small and marginal farmers.

2. Integration of multiple data sources

Modern agriculture generates data from many sources including weather systems, remote sensing, and field-level monitoring. AI integrates these datasets and converts them into simple insights that farmers can act upon. This reduces complexity and supports faster decision-making.

ISSN: 3049-2289

3. Supporting agricultural finance and risk assessment

Agriculture involves financial decisions related to credit, investment, and risk management. AI-driven data analysis can support better assessment of crop conditions and production risks, helping improve confidence in agricultural lending. This creates a stronger link between farming decisions and financial sustainability.

(IV) AI in Indian Agriculture: Data, Digital Platforms and Government initiatives

India is increasingly integrating Artificial Intelligence into agriculture through digital platforms and government-supported initiatives aimed at improving farm productivity and decision-making. AI-based tools are being used to convert data from weather systems, satellite imagery, and field observations into practical recommendations for farmers. This shift reflects a broader movement toward data-driven agriculture where technology supports farmers in managing risks.

1. **Digital Agriculture Mission and Data-driven farming**

The Government of India has launched the **Digital Agriculture Mission (2021–2025)** to promote the use of emerging technologies such as AI, remote sensing, and data analytics in agriculture. The initiative focuses on creating digital infrastructure that enables farmers to access advisory services, improve planning, and make informed decisions based on real-time information. AI-supported platforms developed under this vision aim to simplify complex agricultural data for everyday farm use.

2. AgriStack and Farmer-centric digital ecosystem

The concept of **AgriStack** is designed to build a unified digital ecosystem for agriculture by integrating farmer data, land records, and crop information. This framework enables AI-based advisory systems to deliver more personalized recommendations related to crop planning, irrigation, and risk management. By improving data availability, AgriStack supports better decision-making at both farmer and institutional levels.

3. PM-KISAN and digital integration

While **PM-KISAN (Pradhan Mantri Kisan Samman Nidhi)** primarily provides direct income support to farmers, it has also contributed to building a verified digital database of farmers across the country. This digital foundation creates opportunities for integrating AI-based advisory services and financial support systems in the future. Reliable farmer data strengthens the ability of digital platforms to provide targeted recommendations.

4. e-NAM and market decision support

The **National Agriculture Market (e-NAM)** platform supports farmers by improving access to market information and transparent price discovery. AI and data analytics can further strengthen such platforms by helping farmers understand price trends and make better selling decisions. Improved market intelligence reduces uncertainty and supports income stability.

5. AI for climate resilience and risk reduction

Government-supported digital agriculture initiatives increasingly focus on climate resilience by using AI to analyse weather patterns and provide early warnings related to pest outbreaks and extreme climate events. These systems help farmers plan preventive actions, reducing crop losses and improving overall farm sustainability.

(V)The human experience & AI: Working together

Despite technological advancements, farming remains deeply dependent on human judgment and local knowledge. AI provides analysis and recommendations, but farmers interpret these insights based on their experience and field realities.

The combination of technology and human expertise creates stronger and more resilient decision-making.

1. AI as an Advisor, not a replacement

AI supports decision-making but does not replace a farmer's practical understanding of his land and crops. Farmers remain responsible for final decisions related to farming operations. This partnership approach ensures that technology enhances rather than disrupts traditional farming practices.

2. Building confidence through better information

Access to accurate and timely information helps farmers reduce uncertainty and plan with greater confidence. AI simplifies complex data and presents it in a usable form, allowing farmers to act proactively. Better information leads to better risk management and improved outcomes.

3. Future of farming decisions

The future of agriculture is likely to involve closer integration between digital technologies and traditional farming knowledge. As AI tools become more accessible, farmers will increasingly rely on data-supported decision-making. This partnership between intelligence and experience will shape more sustainable and efficient agriculture.

Can AI actually lift farmer income in India?

AI can contribute to improving farmer income when three critical systems work together - data, access, and markets.

First, a strong data pipeline is needed, where reliable farm-level information such as geo-tagged crop data, weather updates, and pest or disease signals helps generate timely advisory alerts and more precise input use. Accurate data allows farmers to make decisions that reduce risk and avoid unnecessary expenditure.

Second, an effective access pipeline ensures that technology is usable and affordable. Rental-based drone services, local-language mobile applications, village-level service providers, and simple digital advisory tools help farmers adopt AI solutions without requiring high upfront investment or advanced technical skills. This improves inclusion, especially for small and marginal farmers.

Third, a strong market pipeline connects production decisions to better income outcomes. AI-enabled quality testing, traceability systems, buyer discovery platforms, and logistics support help farmers reach better markets and secure improved prices. Evidence from pilot projects and field studies indicates that when these three elements work together, often supported by Farmer Producer Organizations (FPOs) or Custom Hiring Centres (CHCs), farmers experience reduced input wastage and higher realised income.

AI as a Farmer's decision partner: Key impact areas

- Better weather forecasting and climate risk planning
- Optimized input use and reduced production costs
- Early pest and disease detection for timely action
- Improved market intelligence and price decision-making
- Stronger financial confidence through data-driven agriculture

Conclusion

Agriculture is entering a new phase where decisions are supported not only by experience but also by data and technology. Artificial Intelligence is emerging as a reliable decision partner that helps farmers manage risks, improve efficiency, and make more informed choices. However, the real impact on farmer income will depend on how effectively data systems, access mechanisms, and market linkages work together to support everyday farming decisions. As agriculture

ISSN: 3049-2289

becomes increasingly data-driven, the most successful farming systems will be those where human experience and artificial intelligence function as partners, creating more resilient, sustainable, and economically viable agricultural ecosystems.

References:

1. Human Centered Weather Forecasts Initiative: University of Chicago Institute for Climate & Sustainable Growth (2025) https://humancenteredforecasts.climate.uchicago.edu/forecasting-the-onset-of-the-indian-monsoon/

2. CDAC to pilot AI-driven precision farming project in Jharkhand: https://www.ptinews.com/story/business/cdac-to-pilot-ai-driven-precision-farming-project-in-jharkhand/3262186

3. Wadhwani AI : AI for Humanity: https://www.wadhwaniai.org/impact/agriculture-solutions/

4. DeHaat is a full-stack agricultural technology platform : https://frontiertech.niti.gov.in/story/dehaats-ai-enabled-agriculture-network-driving-market-access-and-efficiency-for-1-8-million-farmers/

5.Cropin - World's most innovative and widely deployed AI platform for food and agriculturehttps://www.cropin.com/about/

6. Future Farming in India A Playbook for Scaling Artificial Intelligence in Agriculture (August 2025) : https://www.weforum.org/publications/future-farming-a-playbook-for-scaling-artificial-intelligence-in-agriculture/

AGRICULTURE BULLETIN
ISSN: 3049-2289

Effects of Neonicotinoids on Non-Target Pollinators

S. Poornima
Assistant Professor in Agricultural Entomology, Department of Crop Protection, Nalanda College of Agriculture, M.R. Palayam, Trichy-621104, Tamilnadu, India.

Introduction

Pollinators are essential to agricultural systems and natural ecosystems because they help flowering plants reproduce. According to estimates, insects are the primary source of animal-mediated pollination, which is required for at least 75% of the world's food crops. Butterflies, solitary bees, bumblebees (*Bombus spp*.), western honey bees (*Apis mellifera*), and other wild insects are crucial for preserving biodiversity and agricultural output.

However, extensive decreases in pollinator populations have been reported in North America, Europe, and certain regions of Asia in recent decades. Numerous interrelated stressors have been identified, including as pesticide exposure, infections, habitat loss, and climate change. Neonicotinoids, a family of systemic insecticides that were first used in the 1990s, have drawn special attention. Neonicotinoids are now the most frequently used insecticides in the world due to their high effectiveness against crop pests and ease of application, particularly when used as seed treatments.

Neonicotinoids are specialized to insect pests, but there is mounting evidence that they can also negatively impact pollinators who are not targets. The processes which neonicotinoids affect pollinators are examined in this paper, together with the empirical data from field and lab investigations and the ecological and regulatory ramifications.

Overview of Neonicotinoids

In the central nervous system of insects, neonicotinoids such as imidacloprid, clothianidin, thiamethoxam, and acetamiprid function as agonists of nicotinic acetylcholine receptors (nAChRs). They cause overstimulation, paralysis, and death by attaching to these receptors in an irreversible manner. Neonicotinoids are systemic like contact insecticides. When used as soil drenches or seed coatings, they are taken up by plant tissues and distributed throughout the plant, including pollen and nectar. As a result, even when pesticides are used before to flowering, pollinators may be exposed over time through foraging.

The possibility of environmental contamination and exposure through non-crop plants, surface water, and dust during planting is further increased by their water solubility and soil persistence.

Routes of Exposure in Non-Target Pollinators

Neonicotinoids can reach non-target pollinators in a number of ways:

1. Consumption of pollen and nectar from treated crops.
2. Dust drift when treated seeds are being planted.
3. Contaminated wildflowers growing near agricultural fields.
4. Water sources with traces of pesticides.
5. Exposure of the soil to ground-nesting bees.

These various exposure pathways lead to both acute and long-term exposure situations, frequently at levels below the lethal threshold.

Lethal Effects

In pollinators, high neonicotinoid doses can result in acute death. According to lab tests, some neonicotinoids are very hazardous to honey bees both orally and by touch. Under regulated circumstances, even small dosages can be fatal, according to LD50 values.

However, compared to laboratory toxicity tests, field-realistic concentrations are frequently lower. Thus, although there have been reports of acute death events (especially during planting seasons as a result of polluted dust), sublethal and chronic impacts are of greater concern.

Sublethal Effects

One of the most important factors in assessing neonicotinoid risk is sublethal exposure. These pesticides has the ability to disrupt important activities that are essential for colony survival and successful reproduction, even at low concentrations.

1. Impaired Navigation and Foraging

Neural circuits implicated in memory and learning are impacted by neonicotinoids. Foraging bees' decreased homing ability has been linked in studies to higher mortality rates outside of the hive. Colony resource intake and foraging efficiency are decreased by impaired navigation.

2. Reduced Reproductive Success

Chronic exposure has been associated with smaller colony growth and decreased queen production in bumblebees. Under exposure conditions, solitary bees show reduced nesting success and young survival.

3. Altered Immune Function

Neonicotinoids may reduce immunological responses, making people more vulnerable to viral infections and organisms like *Nosema spp*. Pathogens and insecticides may work in concert to increase the effects at the colony level.

4. Behavioral and Cognitive Disruption

Exposure might hinder the growth of larvae, change communication behaviors (such as honey bees' ability to precisely waggle dance), and decrease the efficiency of pollen collecting.

Field Studies and Ecological Context

Compared to laboratory experiments, field-based research yields more variable results. While some large-scale studies reveal low impact under specific environmental conditions, others report quantifiable detrimental effects on wild bee abundance and reproductive performance in treated settings.

Differences in the outcomes may derive from differences in:

- Crop type and application technique
- The landscape's complexity
- Species-specific sensitivity
- The length of exposure

Additionally, while they are less researched, wild pollinators frequently show more sensitivity than controlled honey bees.

Population-Level and Ecosystem Implications

Pollinators have a major impact on crop production and environmental stability. Although they might not result in immediate die-offs, sublethal impacts that impair colony performance can contribute to long-term population decreases.

Decreased variety of pollinators could:

- Reduced effectiveness of pollination
- Reduced yields of crops
- Disrupt networks of pollinators and plants
- Make ecosystems less resilient to environmental change

Synergistic losses could result from the combined effects of insecticides, habitat loss, and climate stress.

Regulatory Responses

In a number of areas, regulatory action has been motivated by worries about pollinator health. Certain neonicotinoids used outdoors are subject to limitations and partial prohibitions imposed by the European Union. Sublethal and chronic exposure measurements have become more and more integrated into risk assessment systems.

Global regulatory measures vary, though, and discussions about pest resistance, alternative pest control methods, and agricultural trade-offs are still ongoing.

Conclusion

One of the pesticide classification that has been investigated the most in relation to pollinator health is neonicotinoids. Although they are useful tools for controlling pests, there is growing evidence that they can harm non-target pollinators through both lethal and sublethal methods. Colony development, immunity, reproduction, and navigation can all be negatively impacted by long-term exposure at field-realistic concentrations. Precautionary management is necessary due to the possibility of population-level consequences, even though the severity of effects differs depending on thespecies and environmental setting.

Ecological sustainability and agricultural productivity must be balanced in future policy decisions. Strategies for habitat improvement, decreased reliance on preventative seed treatments, and integrated pest management (IPM) may offer approaches to mitigate threats to vital pollinator communities.

AGRICULTURE BULLETIN
ISSN: 3049-2289

Uses of Honey Bee Pollen

Dr. M. Devi
Associate Professor (Agricultural Entomology) MIT College of Agriculture and Technology, Musiri.

As medicine

In order to desensitize allergic patients, pollen is usually collected directly from the plants, to allow proper identification and purity. A pollen extract is then injected subcutaneously. Desensitization through ingestion of pollen is claimed, but has not received any scientific confirmation. For treatment of various prostate problems, pollen is usually prescribed in its dry pellet form as collected by the bees. Pollen from different countries or regions seems to work equally well. However, pollen has not been officially recognized as a medicinal drug. Since the consumption of pollen appears to improve the general condition and food conversion rate in animals as well as people, its support in accompanying other cures should be solicited more frequently. There may be other medicinal uses in traditional medicine which, however, have not been published in readily accessible journals.

As food

The major use of pollen today is as a food or, more correctly, as a food supplement. As stated earlier its likely value as a food for humans is frequently overstated and has never been proven in controlled experiments. That it is not a perfect food, as stated on many advertisements, food packages and even in various non-scientific publications should be obvious. Its low content or absence of the fat soluble vitamins should be sufficient scientific evidence. This does not mean that its consumption may not be beneficial, as has been shown scientifically with various animal diets.

Pollen has been added to diets for domestic animals and laboratory insects resulting in improvements of health, growth and food conversion rates. Chickens exhibited improved food conversion efficiency with the addition of only 2.5% pollen to a balanced diet. Beekeepers too, feed their colonies with pure pollen, pollen supplements or pollen substitutes during periods with limited natural pollen sources. The relatively high cost of pollen suggests the need for a detailed feasibility analysis of pollen as food additive or supplement.

Only a good mixture of different species of pollen can provide the average values mentioned in the tables describing the composition of pollen. The real value of diversity of pollen content, however, lies in the balance of these nutrients and the synergistic effect of the diversity as well as more subtle effects or characteristics related to their origin rather than their quantitative presence. Those very subtle characteristics and sensitive compounds are easily lost with improper storage and processing, something to carefully watch when making or buying quality products containing "bee" pollen.

Beebread

Traditional beekeeping cultures with honeybees or stingless bees, usually appreciate the stored pollen, i.e. beebread. Its characteristic sour taste together with brood and honey is a delicacy consumed directly during harvesting. The pollen stored by honeybees undergoes a lactic acid fermentation and is thus preserved. This final storage product is called beebread. This improves the nutritional value of pollen and avoids the need for freezing. Natural and homemade beebread will keep for a considerable time and can easily be transported to the market and served - even in small quantities - as an excellent source of otherwise scarcely available nutrients. It can be sold clean and by itself or immersed in honey to make it more attractive in taste. Small pieces of

ISSN: 3049-2289

comb can thus be sold or given away as candy. The nutritional value of beebread is much higher in places where limited food variety or quantity create nutrient imbalances. It is particularly children who might benefit the most from regular pollen supplements in their diets.

In cosmetics

Pollen has only recently been included in some cosmetic preparations with claims of rejuvenating and nourishing effects for the skin. The effectiveness has not been proven, but there is a considerable allergy risk for a large percentage of the population. Therefore this practice is not very advisable since it excludes a large proportion of potential customers and puts others at risk of having or developing very unpleasant allergic reactions. Including alcoholic or aqueous pollen extracts in cosmetic formulations appears to cause no or only rare allergic reactions. While little is known about the effectiveness of such extracts, they are still the preferred method of preparation for formulations in the cosmetic industry.

For pollination

Hand and bee-collected pollen have been used for mechanical or hand pollination. The viability of hand-collected pollen can be maintained for a few weeks or months by frozen storage. Bee-collected pollen however, starts losing its viability after a few hours and increasingly with age. It is believed that some of the enzymes added by bees during foraging inhibit the pollen's ability to germinate on the flower stigma. Large-scale applications with mechanical dusters or by using dusted honeybees for dispersion were only moderately successful.

For pollution monitoring

Since the 1980's, experiments have shown that pollen collected by honeybees reflects environmental pollution levels when examined for metals, heavy metals and radioactivity. Contaminants can be quantified and sampling may be cheaper than most standard methods currently in use. Attempts have also been made to use pollen-collecting honeybees for the identification of potential mining area. The same effect of accumulating aerial deposits and selective plant secretions of minerals beneficial when used to monitor pollution control becomes a hazard if pollen from heavily polluted areas is used for human or animal consumption.

Pollen collection

Extreme care should be taken that pollen is not contaminated by bees collecting from flowers treated with pesticides. During, and for several days or weeks after treatment of fields or forests in an area of several square kilometres (in a circle of at least 3-4 2 km diametre) around the apiary, no pollen should be collected. This is independent of the method of pesticide application. Even systemic pesticides have been shown to concentrate in pollen of, for example coconut (Rai *et al*., 1977). Since a pollen pellet is collected from many flowers, even small quantities of pesticides per flower can be accumulated rapidly to reach significant concentrations. Though pollen pellets are collected before they enter the hive, treatment of colonies for bee diseases, can contaminate the pollen pellets. Though, for example, cleaning of debris from the hive and bees regurgitating syrup, nectar or honey during collection of the pellets.

Pollen pellets are removed from the bees before they enter the hive. There are many designs of pollen traps some easier to clean and harvest, others more efficient or easier to install. The efficiency rarely exceeds 50%, i.e. less than 50% of the returning foragers loose their pollen pellets. Bees are ingenious in finding ways to avoid losing their pellets, like small holes or uneven screens and may even rob pollen from the collecting trays, if access is possible. Under some circumstances, pollen collection methods and regimes may interfere with normal colony growth or honey production. Therefore, standard beekeeping manuals should be consulted for the timing of collections (Dadant, 1992).

Pollen should be collected daily in humid climates but less frequently in drier climates. To avoid deterioration of the pollen and growth of bacteria, moulds and insect larvae, pollen should be dried quickly. Ants can remove considerable amounts from pollen traps. Krell (personal observations) reports that losses can be up to 30% in temperate climates.

Pollen needs to be dried to less than 10% moisture content (preferably 5 % or 8% according to some laws) as soon as possible after harvesting. A simple method uses a regular light bulb suspended high enough above a pollen carton or tray so that the pollen does not heat to more than 40 or 45 ^{0}C. For solar drying, the pollen itself should be covered to avoid direct sunlight and overheating.

After drying, the pollen needs to be cleaned of all foreign matter. A tubular tumbler made out of a wire mash with a fan can clean considerable quantities of pollen pellets. Simpler winning methods can be used too. Benson (1984) give very good accounts on trapping and subsequent processing of pollen. Most types of pollen traps are currently only fitted to standard frame hives. are fitted to traditional log, clay or straw hives, small modifications are necessary.

Beebread is usually found on brood combs or combs near the brood nest. Available quantities are normally very small and inadvertently the brood comb and sometimes the whole colony are destroyed during harvest. A team of Russian scientists described a nondestructive means of extracting beebread from combs, harvesting 300-600 kg per year from 1500 colonies. Some races of bees will store large quantities of beebread when colonies have become queenless, or the brood nest and/or plenty super space, are above an empty box with combs. Such manipulations will be more difficult or impossible with most traditional bee hives but modifications may be worthwhile. As mentioned earlier, beebread can also be made at home from bee-collected pollen.

Close up of a lily flower with pollen

Pollen buying

Quality control of pollen is difficult and under most circumstances impossible. It is therefore very important that the buyer knows the supplier well and can trust him. A reliable supplier should have all necessary storage and processing facilities and use them. Furthermore the production area, not only the residence or processing centre, should be free of agrochemicals and industrial pollution (and chemical treatments of the colonies). There are less and less of these regions in industrialized countries and a vast array and quantity of agrochemicals are now being used even in developing countries. More remote zones have problems with proper storage and transport and may require special collection and storage centres.

Buying processed products requires similar caution. The processor has to use gentle processing procedures to maintain those subtle qualities of pollen, which earned it its collected during four days. This type of trap is placed between bottom board and brood reputation. The buyer, whether consumer, retailer or processor has to be very careful and pay considerable attention to all handling and processing from the field collection to the final product. A

ISSN: 3049-2289

truthful label could describe all the essential steps taken in order to guarantee the quality of the product. The need for highly ethical behaviour and knowledge at all levels is a requirement to be considered seriously, by anyone starting in this business, be it producer, processor or distributor. Forming a self-controlling organization, which certifies and controls producers and manufacturers may be useful or necessary to minimise fraud or avoid unreliable quality.

Storage

Pollen, like other protein rich foods, loses its nutritional value rapidly when stored incorrectly. Fresh pollen stored at room temperature loses its quality within a few days. Fresh pollen stored in a freezer loses much of its nutritive value after one year. Longer, improper storage leads to the loss of a few particular amino acids, which cause deficiencies in brood rearing (Dietz, 1975). When dried to less than 10% (preferably 5%) moisture content at less than 45°C and stored out of direct sunlight, pollen can be kept at room temperature for a several months. The same pollen may be refrigerated at 5°C for at least a year or frozen to –15°C for many years without quality loss as tested by feeding to honeybee colonies and recording brood rearing rate (Dietz and Stephenson 1975 and 1980). Since sunlight, i.e. UV radiation, destroys the nutrient value of pollen, other more subtle characteristics probably suffer worse damage. Storage of dry pollen in dark glass containers, or in dark cool places, is therefore a requirement.

ISSN: 3049-2289

From Mandis to Mobile Networks: The Digital Rewiring of Agricultural Markets

Prof. Manasa Gowda[1], [2]Roshini, [3]Anjali M

[1]Assistant Professor, School of Media Studies, Garden City University, Bangalore, Karnataka. Orcid ID: 0009-0008-4771-1850

[2,3]II BSC Visual Communication, Garden City University, Bangalore, Karnataka

For generations, the agricultural marketplace revolved around physical mandis, local traders, and word-of-mouth networks. Today, that landscape is rapidly evolving. Farmers are stepping into a digitally connected ecosystem where smartphones serve as trading desks, advisory hubs, and networking tools. The transformation goes far beyond social media promotion—it reflects a structural shift toward digital networking, transparency, and entrepreneurship in agriculture.

Across India and globally, specialized platforms are enabling farmers to move closer to buyers, access real-time information, and reduce reliance on traditional intermediaries. This process of disintermediation is reshaping bargaining power in favor of producers, offering greater price discovery and direct engagement with markets.

One major space where farmers are building professional visibility is LinkedIn. Once considered a corporate platform, it now hosts agribusiness leaders, agri-tech innovators, exporters, and policymakers. Progressive farmers use it to showcase sustainable practices, explore export partnerships, and connect with startups offering digital solutions. Agriculture is increasingly being positioned not merely as cultivation, but as enterprise.

At the marketplace level, platforms such as Kisan Network are directly linking farmers with verified buyers. By cutting out multiple layers of commission agents, such platforms improve transparency and help farmers negotiate better rates. The digital interface simplifies transactions while preserving traceability—an essential feature in modern supply chains where consumers demand accountability.

Similarly, eNAM, the National Agriculture Market, integrates mandis across states into a unified online trading portal. Farmers gain access to a broader pool of traders, which enhances competitive bidding and price realization. Instead of being confined to local buyers, producers can participate in a national digital marketplace.

Knowledge networking is equally vital. Platforms like AgriFarming provide practical guides on crop selection, pest management, livestock care, and agribusiness planning. In a sector where extension services may not always reach remote regions, digital advisory resources bridge crucial information gaps. Farmers learn from shared experiences and adapt techniques suited to their soil and climate.

Technology-driven advisory and input services are expanding through companies such as AgroStar and DeHaat. These platforms combine agronomy expertise, input supply chains, and output market linkages within integrated ecosystems. A farmer can receive crop-specific advice, purchase inputs, and secure buyers—often within a single digital framework. This integrated model reflects a new form of rural entrepreneurship supported by data and connectivity.

For commodity producers, AgriBazaar offers digital grain trading with quality testing and warehousing linkages. Such systems strengthen trust between sellers and buyers while improving efficiency in bulk transactions. On a global scale,

ISSN: 3049-2289

Farmers Business Network demonstrates how data-sharing and collective purchasing can empower farmers through price transparency and collaborative negotiation.

What unites these platforms is their emphasis on networks rather than isolated transactions. Farmers are no longer passive price takers operating at the end of a long supply chain. They are becoming informed decision-makers—tracking market trends, exploring diversified revenue streams, and engaging in strategic partnerships.

Beyond trade and advisory services, digital networking is also fostering financial inclusion. Access to online transaction histories and digital records strengthens farmers' credibility when applying for loans or crop insurance. Fintech integrations within agri-platforms are gradually reducing paperwork barriers, enabling quicker access to credit and risk management tools.

Moreover, data analytics is emerging as a silent ally. Platforms analyze weather forecasts, soil data, and market demand patterns to generate predictive insights. Farmers can adjust sowing schedules, diversify crops, or plan storage strategies based on real-time intelligence. This shift from reactive to proactive decision-making represents a profound cultural change within rural economies.

Youth participation in agriculture is also receiving a boost. Digitally literate young farmers are blending traditional knowledge with technological agility. They manage online listings, negotiate with buyers, and promote farm produce while elders focus on cultivation expertise. This intergenerational collaboration is redefining the image of farming as innovative and aspirational.

Of course, challenges remain. Digital literacy gaps, connectivity issues, and trust in online transactions must be addressed. Infrastructure investment, training initiatives, and cybersecurity awareness are essential to ensure inclusive growth. Yet the direction is clear: agriculture is integrating with the digital economy. The farm gate is no longer the boundary of opportunity.

In this emerging landscape, success depends not only on rainfall and soil quality but also on connectivity and adaptability. Farmers who cultivate digital networks alongside their crops are positioning themselves at the forefront of a new agri-marketplace—one defined by transparency, entrepreneurship, and empowered participation.

The marketplace has expanded beyond the mandi. It now thrives in digital networks where farmers connect, collaborate, and compete on their own terms—harvesting not just crops, but opportunity in a connected world.

AGRICULTURE BULLETIN
ISSN: 3049-2289

Biochar: Soil Amendment for Improving Nutrient Use Efficiency

Sameer Shrivastava*, Ankit Yadav, Waris Ali
Department of Agronomy, Institute of Agricultural Sciences, Banaras Hindu University, Varanasi-221005, India
Department of Agricultural Economics, Institute of Agricultural Sciences, Banaras Hindu University, Varanasi-221005, India
Department of Extension Education, Institute of Agricultural Sciences, Banaras Hindu University, Varanasi-221005, India

1. Introduction

Nutrient use efficiency (NUE) is a fundamental component of sustainable agricultural systems, as it determines how effectively crops utilize applied nutrients for growth and productivity. Efficient nutrient management not only enhances crop yield but also minimizes environmental degradation associated with nutrient losses. Among the essential plant nutrients, nitrogen (N), phosphorus (P), and potassium (K) play a crucial role in crop development; however, their utilization efficiency in agricultural systems remains relatively low. The average use efficiency of applied nutrients is estimated to be approximately 30–40% for nitrogen, 15–20% for phosphorus, and 50–60% for potassium. A significant proportion of these nutrients is lost through processes such as leaching, surface runoff, volatilization, and gaseous emissions, resulting in reduced fertilizer efficiency and increased environmental pollution.

The interactions among soil properties, plant physiology, water availability, and nutrient management practices greatly influence NUE in cropping systems. Conventional mineral fertilizers, although effective in supplying nutrients, often fail to contribute organic carbon to the soil and are highly susceptible to nutrient losses. Consequently, improving nutrient retention and nutrient availability in soils has become a major challenge for researchers and agricultural practitioners.

In recent years, biochar has emerged as a promising soil amendment for improving soil health and enhancing nutrient use efficiency. Biochar is a stable, carbon-rich material produced through the pyrolysis of biomass under limited oxygen conditions. Due to its high surface area, porous structure, and strong adsorption capacity, biochar can improve soil physical, chemical, and biological properties. These characteristics help increase nutrient retention, reduce nutrient leaching, enhance microbial activity, and improve overall soil fertility. Therefore, the application of biochar has gained considerable attention as a sustainable strategy to enhance nutrient use efficiency and promote environmentally sound agricultural production systems.

What is biochar?

Biochar is a carbon rich, fine grained and porous product remain after plant biomass has undergone a thermochemical conversion process (pyrolysis) at higher temperatures (350–600°C) in an oxygen-poor or oxygen-deficient atmosphere. A stable and resistant organic carbon-rich amendment to enhance the physical, chemical, and biological qualities of soil, it is a byproduct of the pyrolysis of organic materials such wood, rice husk, rice straw, leaves, grasses, crop residues, and manure. Table 1 shows the relative nutritional content of biochar made from various feedstocks. According to Table 1, when used exclusively as a fertilizer source in the crop field, biochar does not contain enough nutrients to satisfy all of the nutrient demands of plants.

ISSN: 3049-2289

Table-1: Different feedstock used for biochar preparation and Total C, N, P and K content

Feedstock	Total C (g/kg)	Total N (g/kg)	Total P (g/kg)	Total K (g/kg)
Rice husk	437.3	1.0	0.64	1.7
Rice straw	499.2	1.22	0.85	2.1
Wheat straw	690	1.55	0.72	1.7
Corn cob	811	6.4	0.92	0.4
Sugarcane bagasse	673	3.0	2.65	-
Wood	708	10.9	6.8	0.9
Pine chip	770	1.7	0.58	2.8
Poultry litter	380	20	25	22.1

This article explores the mechanisms through which biochar enhances NUE and evaluates its practical applications across different agroecosystems.

2. Properties of biochar relevant to nutrient use efficiency

➢ Surface area and porosity

Nutrient retention is greatly aided by the porous structure of biochar, which varies according to the feedstock and pyrolysis conditions. The biochar's ability to absorb nutrients, especially cations like potassium (K^+) and ammonium (NH_4^+), is increased by higher surface areas and porosity, which lowers nutrient leaching and improves plant availability.

According to studies, biochar produced at temperatures between 500 and 700 degrees Celsius tends to have more surface areas and porosity, which is associated with superior nutrient retention qualities, which improved NUE.

➢ Cation exchange capacity (CEC)

Biochar's ability to improve CEC is crucial for nutrient retention and availability. Soils with higher CEC can hold more cations like potassium (K^+), magnesium (Mg^{2+}), and calcium (Ca^{2+}), making these nutrients more accessible to plants. Biochar enhances the CEC of soils, especially in sandy or degraded soils with low natural CEC (Glaser et al., 2002). Data from research done by Major et al. (2010) demonstrated that biochar applications raised CEC by up to 20%, resulting in greater retention of key nutrients in tropical soils. This increase in nitrogen retention can minimize fertilizer inputs and enhance NUE.

➢ pH modification

Particularly in acidic soils, biochar can serve as a liming agent, raising the pH of the soil and enhancing nutrient availability. This can help lower the toxicity of aluminum (Al^{3+}) and increase the availability of phosphorous (P) and other nutrients. A study by Novak et al. (2009) demonstrated how biochar-induced pH changes can contribute to improved NUE by showing that applying biochar increased the pH of acidic soils by 1-2 units, significantly improving P availability and increasing crop yields by 15-25% in P-deficient soils.

3. Mechanism of biochar in improving nutrient use efficiency (NUE)

Biochar improves nutrient use efficiency (NUE) through several physical, chemical, and biological mechanisms that enhance nutrient retention, availability, and uptake by plants. These mechanisms collectively reduce nutrient losses and improve soil fertility, thereby increasing the effectiveness of applied fertilizers.

➢ Improvement in soil physical properties

Biochar has a highly porous structure and large surface area, which significantly improves soil physical characteristics such as soil structure, aeration, and water-holding capacity. Improved soil aggregation enhances root growth and facilitates better nutrient uptake by plants. Additionally, increased water retention helps maintain soil moisture for longer periods, which supports nutrient dissolution and availability to crops.

ISSN: 3049-2289

- **Enhanced nutrient retention and reduced leaching**

Biochar contains a high cation exchange capacity (CEC), enabling it to adsorb and retain positively charged nutrient ions such as ammonium (NH_4^+), potassium (K^+), calcium (Ca^{2+}), and magnesium (Mg^{2+}). By holding these nutrients on its surface, biochar reduces nutrient losses through leaching and runoff. This retention ensures a gradual release of nutrients into the soil solution, making them available to plants over a longer duration.

- **Reduction of nitrogen losses**

Nitrogen losses from agricultural soils commonly occur through leaching of nitrate (NO_3^-), volatilization of ammonia (NH_3), and denitrification. Biochar helps reduce these losses by adsorbing ammonium and nitrate ions and improving soil aeration, which can limit denitrification processes. As a result, more nitrogen remains available in the root zone for plant uptake, thereby improving nitrogen use efficiency.

- **Influence on soil microbial activity**

Biochar provides a suitable habitat for beneficial soil microorganisms due to its porous structure and large surface area. These microorganisms play an essential role in nutrient cycling processes such as nitrogen fixation, nitrification, mineralization, and phosphorus solubilization. Enhanced microbial activity promotes the conversion of nutrients into plant-available forms, thereby improving nutrient uptake and NUE.

- **Improved phosphorus availability**

In many soils, phosphorus becomes fixed by calcium, iron, or aluminum compounds, making it unavailable to plants. Biochar can reduce phosphorus fixation by altering soil pH and interacting with soil minerals. It also increases the availability of phosphorus by adsorbing phosphate ions and releasing them slowly into the soil solution, thereby enhancing phosphorus use efficiency.

- **Soil pH modification**

Biochar generally has an alkaline nature, which can help neutralize acidic soils. By increasing soil pH, biochar improves nutrient availability and reduces toxicity of certain elements such as aluminium and manganese. A balanced soil pH promotes better nutrient uptake by plants and contributes to improved NUE.

- **Slow nutrient release and fertilizer efficiency**

Biochar can act as a nutrient reservoir by absorbing nutrients from fertilizers and gradually releasing them according to plant demand. This slow-release behavior increases fertilizer efficiency and reduces the need for frequent fertilizer applications.

- **Increased root growth and nutrient uptake**

Improved soil conditions created by biochar, such as better aeration, moisture retention, and nutrient availability, promote root development. A well-developed root system can explore a larger soil volume, enabling plants to absorb nutrients more efficiently.

4. Biochar and nutrient cycling

- **Nitrogen cycling**

A major obstacle to increasing NUE is nitrogen losses from agricultural systems, mostly from leaching and volatilization. By lowering nitrate (NO_3^-) leaching, adsorbing ammonium (NH_4^+), and perhaps slowing down nitrification processes, biochar has been demonstrated to affect nitrogen dynamics in soils. Singh *et al.* (2010) showed in a long-term research that adding biochar increased plant nitrogen absorption by 12–20% while decreasing nitrogen leaching by 30–50%. The requirement for frequent nitrogen fertilization is

ISSN: 3049-2289

decreased by biochar's strong affinity for NH_4^+, which helps maintain nitrogen in the root zone.

- **Phosphorus cycling**

Because phosphorus tends to form insoluble compounds with calcium, iron, or aluminum, it is frequently trapped in soils. By lessening these interactions, biochar can increase P availability. The alkaline pH of soils treated with biochar aids in the solubilization of phosphate ions, increasing their availability for plant uptake.

Conclusion

Biochar has emerged as a promising soil amendment for improving nutrient use efficiency in agricultural systems. Its unique physicochemical properties, including high surface area, porous structure, and significant adsorption capacity, contribute to improvements in soil physical condition, nutrient retention, and overall soil fertility. By reducing nutrient losses through leaching, volatilization, and runoff, biochar enhances the availability of essential nutrients to plants and supports more efficient utilization of applied fertilizers. Consequently, the integration of biochar into soil management practices can potentially lower fertilizer requirements while maintaining or improving crop productivity.

Despite its considerable potential, the effectiveness of biochar can vary depending on factors such as feedstock type, pyrolysis conditions, soil characteristics, and crop management practices. Therefore, continued research is required to better understand its long-term effects, optimize application rates, and develop standardized production methods. With appropriate management and site-specific application strategies, biochar can serve as an important tool for enhancing soil health, improving nutrient use efficiency, and promoting environmentally sustainable agriculture.

Challenges and future directions

Despite its potential, several challenges remain in the widespread adoption of biochar for improving NUE. The variability in biochar properties due to differences in feedstock and pyrolysis conditions can lead to inconsistent results in field trials. Furthermore, long-term effects of biochar on soil health and nutrient dynamics are still not fully understood.

Future research should focus on optimizing biochar formulations for specific soil types and crop systems. Studies on biochar's interaction with microbial communities, its impact on greenhouse gas emissions, and its economic feasibility in different regions will also be critical in determining its broader applicability.

References

Biederman, L. A., & Harpole, W. S. (2013). Biochar and its effects on plant productivity and nutrient cycling: a meta-analysis. *GCB Bioenergy*, 5(2), 202-214.

Jeffery, S., Verheijen, F. G., van der Velde, M., & Bastos, A. C. (2011). A quantitative review of the effects of biochar application to soils on crop productivity using meta-analysis. *Agriculture, Ecosystems & Environment*, 144

Novak, J. M., Lima, I., Xing, B., Gaskin, J. W., Steiner, C., Das, K. C., & Schomberg, H. (2009). Characterization of designer biochar produced at different temperatures and their effects on a loamy sand. *Annals of Environmental Science,* 3(1), 195-206.

Singh, B. P., Hatton, B. J., Singh, B., Cowie, A. L., & Kathuria, A. (2010). Influence of biochars on nitrous oxide emission and nitrogen leaching from two contrasting soils. *Journal of Environmental Quality*, 39(4), 1224-1235.

AGRICULTURE BULLETIN
ISSN: 3049-2289

Conservation Agriculture: Farming for The Future

Huchchappa Jamakhandi[1*], Yogesh B M[2] and Prakash Sonnad[3]
[13]Ph.D Scholar, Division of Agronomy, ICAR-IARI, New Delhi
[2]Ph.D Scholar, Division of Agricultural Extension, ICAR-IARI, New Delhi

Introduction

Agriculture today faces a major challenge: producing enough food for a rapidly growing population while conserving natural resources. Continuous intensive cultivation, excessive tillage, residue burning, and monocropping have resulted in soil degradation, declining soil organic matter, water scarcity, and increased production costs. These problems threaten the sustainability of agricultural systems and the livelihoods of farmers.

In this context, Conservation Agriculture (CA) has emerged as an innovative and sustainable farming approach. Conservation agriculture focuses on improving soil health, conserving resources, and maintaining crop productivity while reducing environmental damage. It is increasingly recognized worldwide as a pathway to sustainable agriculture and climate-resilient farming systems (Biplab *et al*., 2023).

What is Conservation Agriculture?

Conservation Agriculture is based on three interlinked principles promoted globally by the Food and Agriculture Organization (Fig 1). (FAO, 2011; 2017):

1. Minimum soil disturbance (zero or reduced tillage)
2. Permanent soil cover (crop residues or cover crops)
3. Crop diversification (crop rotation or intercropping)

According to FAO (2011), CA enhances soil biological processes and improves long-term sustainability by reducing mechanical soil disturbance.

Fig 1. Conservation agriculture principles and benefits

Global Scenario of Conservation Agriculture

Conservation agriculture has expanded rapidly across the world. Currently, it is practiced on about 124.8 million hectares of land globally, representing nearly 8% of the world's arable land (Kassam *et al.,* 2019). Countries such as the United States, Brazil, Argentina, Australia, and Canada are among the major adopters of conservation agriculture.

Conservation Agriculture in India: Area and Distribution

Conservation Agriculture is gradually expanding in India. Recent estimates suggest that nearly 2.5 million hectares in South Asia are under partial CA systems, where at least one crop is grown using no-till practices with or without residue retention. About 80–90% of this area lies in India, which means roughly 2 million hectares are currently under CA-based practices. CA adoption is more common among large-scale farmers, mainly because the required machinery is better suited to larger landholdings and is more accessible to them. Although government subsidies and custom-hiring services are available for CA equipment, smallholder farmers have not fully utilized these opportunities.

ISSN: 3049-2289

Based on the estimated CA area and the average landholding size in Punjab (3.62 ha) and Haryana (2.20 ha), it is estimated that around 700,000 farmers in India practice conservation agriculture. Geographically, CA adoption is largely concentrated in the Indo-Gangetic Plains (IGP), especially in Punjab and Haryana, where rice–wheat cropping systems dominate. It is also practiced to some extent in the Eastern Gangetic Plains, including Bihar, West Bengal, eastern Uttar Pradesh, and Odisha, and in limited areas of southern India. However, CA adoption remains low in rainfed, semi-arid, arid, and mountainous regions (Gupta *et al*., 2021).

In India, conservation agriculture is mainly practiced in rice, wheat, maize, and sugarcane-based cropping systems. It is also used in several other crops such as cotton, mustard, soybean, pigeon pea, groundnut, pulses, vegetables, chickpea, barley, sorghum, and jute.

Table 1. Comparison of Conventional Agriculture and Conservation Agriculture (Source: Bhan *et al*., 2014).

Conventional Agriculture	Conservation Agriculture (CA)
Intensive tillage and frequent soil disturbance	Minimum or zero tillage with least soil disturbance
Higher risk of soil and wind erosion	Greatly reduced soil and wind erosion
Crop residues often removed or burned	Crop residues retained on soil surface as mulch
Low water infiltration and higher runoff	Improved water infiltration and moisture conservation
Dependence on external inputs such as FYM/compost applied ex-situ	Greater emphasis on in-situ organic matter recycling
Green manure incorporated through ploughing	Use of cover crops and surface retention of biomass
Weed control mainly through repeated tillage	Integrated weed management; initial weed pressure may occur
Unrestricted machinery movement leading to soil compaction	Controlled traffic to reduce soil compaction
Mono-cropping or poor crop rotation	Diverse and efficient crop rotations
High dependence on manual labour with operational delays	Mechanized and timely field operations
Lower stress tolerance and higher yield losses under stress	Better stress resilience with lower yield losses
Long-term productivity may decline due to soil degradation	Long-term productivity improves gradually with soil health restoration

Why Conservation Agriculture is Needed?

Soil Degradation

Frequent ploughing breaks soil aggregates and accelerates erosion. India loses significant amounts of fertile topsoil annually. Conservation agriculture reduces erosion and improves soil structure (Lal, 2015).

Water Scarcity

In the Indo-Gangetic Plains, intensive rice cultivation has resulted in declining groundwater levels. Studies by CIMMYT (2016) show that zero tillage and residue retention improve water infiltration and reduce evaporation losses.

Climate Change

Conventional tillage exposes soil organic carbon to oxidation, releasing CO_2 into the atmosphere. Conservation agriculture enhances carbon sequestration and reduces greenhouse gas emissions (Lal, 2015). FAO (2017) highlights CA as a climate-smart agricultural practice.

Rising Cost of Cultivation

Zero tillage reduces fuel and labour requirements, lowering production costs (Jat *et al*., 2014).

ISSN: 3049-2289

The Three Pillars in Practice

1. Minimum Soil Disturbance

Zero-till wheat in the rice–wheat system has shown cost savings and yield stability in North-West India (Jat *et al*., 2014). Research supported by the Indian Council of Agricultural Research (ICAR, 2018) confirms improved soil health under reduced tillage.

2. Permanent Soil Cover

Residue retention acts as a protective layer, reducing soil temperature fluctuations and conserving moisture. FAO (2017) emphasizes that permanent soil cover is critical for maintaining soil organic matter. Technologies such as the Happy Seeder allow direct drilling of wheat without burning rice residues, helping reduce air pollution in Punjab and Haryana (ICAR, 2018).

3. Crop Diversification

Crop rotation with legumes improves nitrogen availability and breaks pest cycles. Diversified systems in the Indo-Gangetic Plains have demonstrated improved sustainability and resilience (CIMMYT, 2016).

Benefits of Conservation Agriculture

- **Improved Soil Health**: Increased soil organic carbon and enhanced microbial activity (Lal, 2015).
- **Better Water Management**: Higher infiltration and reduced runoff (FAO, 2017).
- **Reduced Costs**: Lower fuel consumption and fewer field operations (Jat *et al.,* 2014).
- **Climate Mitigation**: Enhanced carbon sequestration potential (Lal, 2015).
- **Yield Stability**: Greater resilience under climatic stress (ICAR, 2018).

Challenges in Adoption

- Lack of suitable machinery for small farmers
- Competing uses of crop residues for livestock feed and fuel
- Traditional belief that tillage is essential for crop production
- Limited awareness and technical knowledge among farmers
- Shortage of trained manpower and extension support

Addressing these challenges through policy support, training, and research is essential for wider adoption of conservation agriculture.

Conclusion

Conservation agriculture is a sustainable farming approach that enhances soil health, conserves water and nutrients, and maintains crop productivity. Practices such as reduced tillage, crop residue retention, and diversified crop rotations help improve resource use efficiency while reducing production costs and environmental degradation. With increasing challenges like soil degradation, climate change, and rising input costs, conservation agriculture provides a resilient solution for sustainable crop production. Therefore, it represents "farming for the future", ensuring long-term agricultural productivity while protecting natural resources for future generations.

References

Bhan, S., & Behera, U. K. (2014). Conservation agriculture in India–Problems, prospects and policy issues. *International Soil and Water Conservation Research*, 2(4), 1-12.

Biplab, M., Imtiyaz, M., Das, S., Ali, M., Debnath, S., Alam, B., Ram, A., & Arunachalam, A. (2023). *Conservation Agriculture: Global Scenario, Opportunities and Challenges.*

CIMMYT. (2016). *Sustainable Intensification in the Indo-Gangetic Plains.* CIMMYT.

FAO. (2011). *Save and Grow: A Policymaker's Guide to Sustainable Intensification of Smallholder Crop Production.* Food and Agriculture Organization, Rome.

FAO. (2017). *Conservation Agriculture.* Food and Agriculture Organization.

Gupta, N., Pradhan, S., Jain, A., & Patel, N. (2021). *Sustainable Agriculture in India 2021: What We Know and How to Scale Up.* Council on Energy, Environment and Water, New Delhi.

ISSN: 3049-2289

ICAR. (2018). *Conservation Agriculture in India: Status and Prospects.* Indian Council of Agricultural Research, New Delhi.

Jat, M. L., *et al*. (2014). Conservation agriculture in rice–wheat systems of South Asia. *Advances in Agronomy.*

Kassam, A., Friedrich, T., & Derpsch, R. (2019). Global spread of conservation agriculture.

Lal, R. (2015). Sequestering carbon and increasing productivity by conservation agriculture. *Journal of Soil and Water Conservation.*

AGRICULTURE BULLETIN
ISSN: 3049-2289

Bharat Vistaar: India's Ai-Powered Agricultural Transformation

Dr. Potluri Swarnalatha
Teaching Associate, Department of Statistics, APGC, Lam, Guntur.

Introduction

India's agricultural sector is witnessing a historic transformation with the launch of Bharat Vistaar, an Artificial Intelligence (AI)-powered digital agriculture platform introduced on 17 February 2026. This initiative represents a strategic move toward integrating advanced digital technologies into farming practices, ensuring that real-time, reliable and localized advisory services reach farmers across the nation.

The full form of **Bharat-VISTAAR** is **Virtually Integrated System to Access Agricultural Resources**. Bharat Vistaar is designed to bridge the gap between scientific research, government schemes, and field-level agricultural practices. It aims to empower farmers with timely knowledge, reduce risk and improve farm profitability through data-driven decision-making.

Vision and Objectives of Bharat Vistaar

The primary objective of Bharat Vistaar is to create a unified digital ecosystem that integrates weather data, market intelligence, pest surveillance, soil health information, and policy updates into one accessible platform. The initiative focuses on inclusivity, ensuring that small and marginal farmers can access high-quality advisory services without requiring advanced digital literacy.

- Enhancing farmer incomes through informed decision-making.
- Improving climate resilience using predictive analytics.
- Reducing crop losses through early pest and disease warnings.
- Providing transparent market price information.
- Strengthening access to government agricultural schemes.

Role of Artificial Intelligence in Bharat Vistaar

Artificial Intelligence forms the backbone of Bharat Vistaar. The system uses machine learning algorithms, natural language processing, and predictive analytics to provide personalized recommendations to farmers.

- Voice-based advisory system accessible via helpline number 155261.
- AI assistant providing responses in simple and understandable language.
- Real-time weather forecasting and rainfall prediction integration.
- Crop-specific fertilizer and irrigation recommendations.
- Market trend analysis to guide selling decisions.
- Risk alerts for pest outbreaks and climate anomalies.

How the Platform Works

Farmers can call the helpline using basic mobile phones. The AI system processes the farmer's query based on location, crop type, and seasonal data. It then integrates meteorological information, market databases, and agricultural research findings to generate customized advisories.

The platform also connects with digital agricultural databases to provide scheme eligibility status, subsidy updates, and insurance information, making it a comprehensive agricultural companion.

ISSN: 3049-2289

Source: https://www.tractorjunction.com

- Reduced uncertainty in sowing and harvesting decisions.
- Efficient water and fertilizer usage.
- Improved income stability through better market timing.
- Minimized crop losses due to early warnings.
- Strengthened linkage between farmers and policymakers.

Broader Impact on Rural Development

Bharat Vistaar contributes to rural empowerment by democratizing access to agricultural knowledge. By reducing dependency on intermediaries for information, farmers gain autonomy and confidence in their decisions. The initiative also promotes digital literacy and encourages youth participation in agribusiness and agri-tech innovations.

The integration of AI in agriculture is expected to support sustainable farming practices, reduce environmental stress, and align agricultural growth with national development goals.

Future Expansion and Roadmap

The initial rollout includes Hindi and English, with plans to expand into multiple regional languages to ensure nationwide reach. Future developments may include mobile app integration, satellite-based crop monitoring, advanced price forecasting models, and integration with digital payment systems. The government envisions Bharat Vistaar as part of a broader AI-for-Agriculture roadmap that will transform India's farming landscape into a technology-driven, resilient, and globally competitive sector.

Conclusion

Bharat Vistaar symbolizes a new era of smart agriculture in India. By embedding Artificial Intelligence into everyday farming decisions, the initiative bridges the gap between innovation and grassroots agriculture. As climate challenges and market volatility continue to impact farming communities, AI-powered platforms like Bharat Vistaar offer hope for a more secure, productive, and prosperous agricultural future.

References:

Times of India. (2026, February 17). *Agriculture ministry launches Bharat-VISTAAR, a multilingual AI tool for digital farm advisories*.

ChiniMandi. (2026, February 17). *'Bharat-VISTAAR' launched: AI platform for farmers*.

Indian Express. (2026, February 17). *Meet 'Bharati': The government's new AI expert that answers farmers' calls in their own language*.

Times of India. (2026, February 1). *Union Budget 2026: Government to launch multi-lingual AI tool Bharat-VISTAAR for farmers*.

IBC24. (2026, February 1). *Government to launch multilingual AI tool 'Bharat-Vistaar'*.

ISSN: 3049-2289

Precision Agriculture for Circular Economy: Smart Sensors, IoT Platforms, Edge AI/TinyML and Digital Farming

G.T. Patle[1], Anita Devi Ningthoujam[2], Ghanashyam Singh Yurembam[1], D. Jhajharia[1]
[1]Department of Soil and Water Conservation Engineering, College of Agricultural Engineering & Post Harvest Technology, Ranipool, Sikkim-737135
[2]ICAR-CRP on Precision Farming & Micro Irrigation System, CAEPHT-CAU Centre, College of Agricultural Engineering & Post Harvest Technology, Ranipool, Sikkim-737135

1.Introduction

With the advancement of digital technologies, agriculture is undergoing a major transformation into farming practices. Traditional farming often relies on manual observations and uniform input application, which may result in inefficient use of water, fertilizers, and energy. Improved innovative techniques while maintaining the environmental sustainability are required in modern agriculture that increases productivity with major concerns for climate change, declining soil fertility, and increasing food demand. Precision agriculture provides an effective solution by integrating advanced technologies such as smart sensors, Internet of Things (IoT) networks, artificial intelligence, and data analytics. These technologies enable farmers to collect real-time information about soil moisture, crop health, weather conditions, and irrigation performance, allowing them to make better management decisions (Soussi et al., 2024).

Figure 1. Integrated Framework of Precision Agriculture

At the same time, the idea of a circular economy—where resources are used effectively, waste is reduced, and agricultural systems become more sustainable—is becoming more and more popular in the agricultural sector.

Figure 1 shows the Conceptual framework showing how sensors, IoT networks, and AI systems support smart and sustainable agriculture.

2. Smart Sensors in Precision Agriculture

Precision agriculture systems rely on smart sensors. These sensors monitors environmental and soil factors that directly influenc crop development.

2.1. Soil Moisture Sensors

By measuring the amount of water in the soil, soil moisture sensors assist farmers in choosing the best time to irrigate. This reduces crop stress and increases water-use efficiency.

Common soil moisture sensors include:

- Capacitance sensors
- Tensiometers
- Time Domain Reflectometry (TDR) sensors
- Frequency Domain Reflectometry (FDR) sensors

The performance of these sensors may vary depending on soil properties such as texture, salinity, and temperature. Therefore, proper calibration and installation are essential for reliable measurements (Soussi et al., 2024).

ISSN: 3049-2289

2.2. Environmental Sensors

Environmental sensors measure important weather parameters such as:

- Temperature
- Humidity
- Solar radiation
- Rainfall
- Wind speed

These data help estimate evapotranspiration and determine crop water requirements.

2.3. Crop Monitoring Sensors

Crop health is tracked using multispectral cameras and sophisticated optical sensors. These sensors detect changes in plant reflectance caused by nutrient deficiencies, pests, or diseases. Crop vigour is frequently evaluated using vegetation indicators like the NDVI.

3. Internet of Things (IoT) in Agriculture

The Internet of Things allows communication between sensors, devices, and farm through wireless networks. IoT systems enable farmers to automate several farming operations and .monitors agricultural fields remotely.

An IoT-based smart farming system typically includes:

1. Field sensors collecting agricultural data
2. Communication networks transmitting data
3. Data processing platforms (cloud or edge computing)
4. Decision-support systems providing recommendations

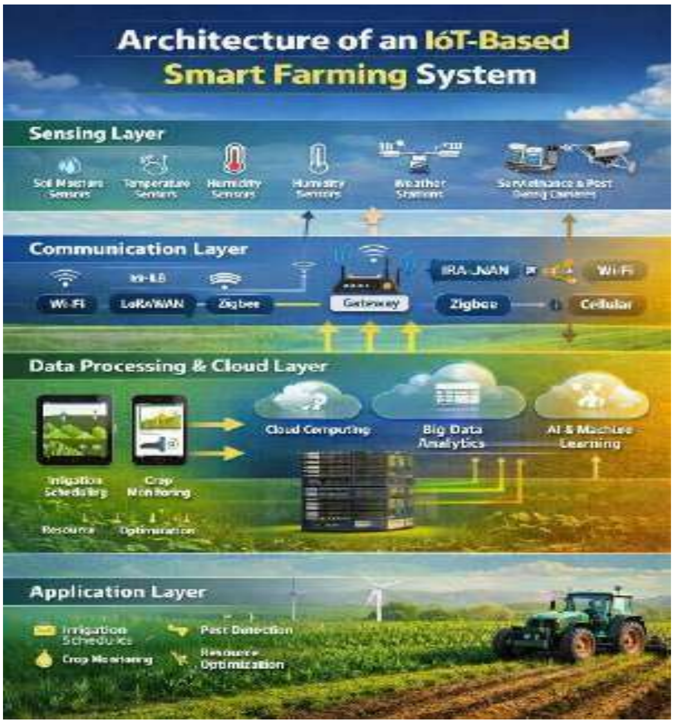


Figure 2. IoT-Based Smart Farming Architecture

Figure 2 shows the typical architecture of IoT-based agricultural monitoring systems.

Table1. Communication Technologies Used in Smart Farming

Technology	Range	Power Use	Data Rate	Application
Wi-Fi	Short	High	High	Greenhouse monitoring
ZigBee	Medium	Low	Medium	Sensor networks
LoRaWAN	Long	Very Low	Low	Field monitoring
NB-IoT	Long	Low	Medium	Smart irrigation

Source: Khan et al. (2024).

4. Edge AI and TinyML in Smart Farming

Artificial intelligence and machine learning are increasingly used to analyze agricultural data collected from sensors, drones, and satellite imagery.

Machine learning algorithms can help in:

ISSN: 3049-2289

- Predicting crop yields
- Detecting plant diseases
- Optimizing irrigation schedules
- Monitoring soil conditions

Cloud computing is the foundation of traditional agricultural monitoring systems. Cloud systems, however, might cause delays and need reliable internet access. On field equipment like gateways or sensor nodes, edge computing handles data locally. As a result, system dependability is increased and latency is decreased.

TinyML allows machine learning algorithms to run directly on low-power microcontrollers embedded in sensors. These technologies enable smart farming solutions even in remote regions with limited connectivity (Jiang et al., 2025).

Table 1. Comparison of Digital Agriculture Technologies

Technology	Function	Advantages	Limitations
Smart Sensors	Monitor soil and environmental parameters	Real-time data collection	Requires calibration
IoT Platforms	Connect devices and transmit data	Remote monitoring	Network dependency
Drones/UAVs	Crop monitoring and imaging	Large area coverage	High cost
Edge AI	Local data processing	Fast response	Limited computing capacity

5. Precision Agriculture and Circular Economy

Circular economy and sustainable resource management are greatly contributed by precision agriculture.

Some of the major benefits of Precision agriculture are

1) **Efficient water use** – Sensor-based irrigation systems reduce water wastage.
2) **Reduced fertilizer loss** – Data-driven nutrient management improves soil health.
3) **Lower pesticide use** – Early pest detection allows targeted treatment.
4) **Waste utilization** – Agricultural residues can be converted into compost or bioenergy.

Figure 3. Sensors–IoT–AI Model for Circular Agriculture

Figure 3 shows the integration of sensing, IoT, and artificial intelligence technologies supporting circular agriculture.

6. Challenges in Adoption

Despite the benefits of precision agriculture, several challenges limit its adoption.

- High initial cost of digital technologies
- Limited digital infrastructure in rural areas
- Lack of technical knowledge among farmers
- Interoperability issues among different devices

Addressing these challenges, collaboration is required among researchers, policymakers, and technology providers.

7. Opportunities for Agri-Entrepreneurship

Precision agriculture technologies also create opportunities for rural entrepreneurs. Possible business models include:

- Sensor installation and monitoring services
- Drone-based crop monitoring
- Smart irrigation advisory systems
- Precision agriculture equipment maintenance

These service-based approaches can support technology adoption while generating employment

8. Conclusion

Precision agriculture is transforming modern farming through the integration of sensors, IoT networks, artificial intelligence, and data analytics. These technologies enable farmers to monitor crop and soil conditions in real time and optimize resource use.

Precision agriculture supports the principles of a circular economy in agriculture by improving efficiency and reducing waste. Promoting sustainable digital farming systems will require ongoing technical innovation and farmer education.

References

1) Soussi *et al*. (2024). *Smart sensors and smart data for precision agriculture.*

2) M. Khan *et al*. (2024). *Internet of Things applications in precision agriculture.*

3) A. Bishnoi *et al*. (2024). *IoT and AI Advancements for Sustainable Agriculture*

4) D. Jiang *et al*. (2025). *Edge-centric agricultural IoT analytics framework.*

AGRICULTURE BULLETIN
ISSN: 3049-2289

Metabolic Pathology in Dairy Animals: Understanding the Hidden Disease Burden

Neetu Nehra* and Sarthak[1]
Department of Animal Husbandry and Dairying, Haryana; [1]Department of Animal Husbandry and Dairying, Punjab

1. The Hidden Health Crisis in Dairy Farms: How metabolic disorders silently affect milk production and animal health.

Modern dairy farming has achieved remarkable improvements in milk production. High-yielding cows and buffaloes can produce impressive amounts of milk, helping meet the growing demand for dairy products. However, this progress has also brought new challenges. Among the most significant yet often overlooked are metabolic disorders—health problems that arise from imbalances in the animal's metabolism.

Unlike infectious diseases, metabolic disorders usually do not spread from one animal to another. Instead, they develop silently within the body, often without obvious signs in the early stages. By the time noticeable symptoms appear, productivity may already be declining. These hidden disorders not only affect animal welfare but also cause significant economic losses for dairy farmers.

2. Why High-Producing Animals Are at Risk

High-producing dairy animals require enormous amounts of nutrients to sustain milk production. During periods such as late pregnancy and early lactation, the animal's body experiences intense metabolic stress. If the nutrients supplied through feed do not perfectly match these demands, metabolic imbalances may occur (Melendez and Vizcaino Serrano, 2024).

In modern dairy systems, animals are often pushed to their physiological limits. Energy, calcium, magnesium, and other nutrients must be carefully balanced. Even small disruptions in this delicate balance can trigger metabolic disorders. Factors such as poor-quality feed, inadequate mineral supplementation, sudden dietary changes, or improper management during the transition period can increase the risk.

3. The Most Common Metabolic Disorders in Dairy Animals

Examples such as Ketosis, Milk Fever, Fatty Liver Syndrome, and Grass Tetany.

Several metabolic disorders commonly affect dairy animals:

- **Ketosis** occurs when the animal experiences an energy deficit during early lactation. The body begins to break down fat excessively, leading to the accumulation of ketone bodies in the blood. Affected animals may show reduced appetite, weight loss, and decreased milk production (Saradhi *et al.,* 2024).
- **Milk fever**, or hypocalcemia, usually occurs soon after calving. It results from a sudden drop in blood calcium levels needed for milk production. Animals may become weak, unable to stand, and require urgent treatment.
- **Fatty liver syndrome** develops when excessive fat accumulates in the liver due to prolonged energy deficiency. This condition impairs liver function and affects overall health and productivity.
- **Grass tetany**, also known as hypomagnesemia, occurs when magnesium levels in the blood fall too low. It often affects grazing animals and can cause muscle tremors, nervousness, and even sudden death.

Although these disorders differ in their causes, they all stem from metabolic imbalances within the body. To better understand how these metabolic disorders affect dairy animals, it is useful to examine them from the perspective of metabolic pathology, which focuses on the structural and biochemical changes occurring within the body.

4. Metabolic Pathology: Understanding Disease Beyond Symptoms

Metabolic disorders in dairy animals are often discussed in terms of nutrition or management, but another important perspective is **metabolic pathology**. This concept focuses on the structural and biochemical changes that occur in tissues when the normal metabolic balance of the body is disturbed.

When dairy animals experience metabolic stress, particularly during the transition period around calving, several organs begin to show subtle but significant pathological changes. One of the most striking examples occurs in the liver during Fatty Liver Syndrome. In this condition, excessive mobilization of body fat leads to the accumulation of lipid droplets inside liver cells. Under microscopic examination, hepatocytes appear swollen and filled with fat vacuoles, impairing the liver's ability to regulate metabolism (Melendez and Pinedo, 2024).

Similarly, mineral imbalances can affect muscle and nerve function. In disorders such as Milk Fever, reduced calcium levels interfere with normal neuromuscular activity, leading to muscle weakness and difficulty standing. These clinical signs reflect underlying physiological and biochemical disturbances within the body.

Clinical pathology further reveals metabolic stress through changes in blood parameters. Elevated ketone bodies during Ketosis, altered liver enzyme levels, or imbalances in minerals such as calcium and magnesium provide important diagnostic clues. Together, these biochemical markers and tissue alterations form the basis of **metabolic pathology**.

By examining both **tissue-level changes and biochemical indicators**, veterinary pathology provides a deeper understanding of how metabolic disorders develop and affect dairy animals. This approach not only improves diagnosis but also supports early detection and preventive herd health management.

5. What Happens Inside the Animal Body: Pathological and biochemical changes occurring in organs and tissues.

Metabolic disorders trigger a series of changes within the body that may not be visible externally. Organs such as the liver, muscles, and nervous system are particularly affected.

For example, in energy-deficient animals, the liver begins processing large amounts of fat released from body reserves. When this process becomes excessive, fat accumulates within liver cells, leading to fatty liver disease (Melendez and Pinedo, 2024). Similarly, calcium and magnesium deficiencies disrupt nerve and muscle function, explaining the weakness or tremors seen in affected animals.

Veterinary pathologists often identify these changes during laboratory examinations of tissues or through biochemical analysis of blood samples. Such findings help explain why the animal's performance declines even when outward signs appear minimal.

6. The Silent Impact on Milk Production

Metabolic disorders have a profound effect on dairy productivity. Animals suffering from metabolic imbalances often produce less milk, experience delayed recovery after calving, and show reduced fertility.

For farmers, these problems translate into economic losses. Lower milk yield, increased veterinary costs, prolonged calving intervals, and even premature culling of animals can significantly affect farm profitability. Because many metabolic disorders develop gradually, farmers may not immediately recognize their true impact.

ISSN: 3049-2289

7.The Metabolic Iceberg: Understanding Subclinical Disease

In many dairy herds, the metabolic disorders that farmers easily recognize represent only a small fraction of the real problem. The visible clinical cases are often just the **"tip of the iceberg."** Beneath the surface lies a much larger number of animals suffering from **subclinical metabolic disorders** that remain unnoticed but still affect productivity and health as shown in figure 1.

For example, while a few cows may show clear symptoms of Ketosis or Milk Fever, many more animals may experience mild metabolic imbalances without obvious signs. These subclinical conditions may not cause immediate illness, but they can quietly reduce milk yield, weaken immune function, and impair reproductive performance.

Subclinical metabolic disorders are particularly common during the transition period around calving, when the animal's metabolism is under intense pressure to support the sudden demand for milk production. During this stage, the body mobilizes large amounts of energy and minerals, and even slight nutritional imbalances can disrupt normal metabolic processes (Dervishi *et al.,* 2021; Melendez and Vizcaino Serrano, 2024).

Because these hidden disorders do not produce dramatic symptoms, they often remain undetected at the farm level. However, laboratory testing and metabolic profiling can reveal subtle biochemical changes in blood or milk, allowing veterinarians to identify animals at risk before clinical disease develops.

Understanding this "metabolic iceberg" concept highlights the importance of regular health monitoring in dairy herds. By identifying subclinical disorders early, farmers and veterinarians can implement timely nutritional and management adjustments that protect animal health, sustain milk production, and prevent larger economic losses.

Figure 1. Conceptual representation of the "metabolic iceberg" in dairy animals illustrating that visible clinical conditions such as Ketosis, Milk Fever, and Grass Tetany represent only the small visible portion of metabolic disorders. Beneath the surface lie subclinical disturbances including negative energy balance and mineral imbalance, along with deeper metabolic pathology characterized by altered blood metabolites (e.g., NEFA- Non-esterified fatty acids and BHBA- β-hydroxy butyric acid), hormonal imbalances, and pathological changes such as hepatic lipid accumulation in Fatty Liver Syndrome. The figure also highlights key detection approaches including clinical pathology, veterinary pathology, and herd-level metabolic monitoring used to identify hidden metabolic stress in dairy herds.

ISSN: 3049-2289

8. Clues from Blood Tests and Laboratory Diagnosis

Many metabolic disorders in dairy animals develop quietly inside the body long before clear symptoms appear. This is where veterinary pathology plays an important role. By examining blood, tissues, and biochemical indicators, veterinarians can uncover hidden metabolic disturbances that might otherwise remain unnoticed.

Clinical pathology helps identify important biochemical markers such as blood glucose, calcium, magnesium, ketone bodies, and liver enzymes. Changes in these parameters often provide early clues about metabolic imbalance. For example, increased ketone bodies in blood or milk can indicate the onset of Ketosis even before the animal shows obvious illness.

Histopathology also provides valuable insights into metabolic disease. In conditions like Fatty Liver Syndrome, microscopic examination of liver tissue reveals excessive fat accumulation within liver cells. These pathological changes explain why affected animals experience reduced appetite, weakness, and decreased milk production. Through such investigations, veterinary pathology helps uncover the internal processes behind metabolic disorders and supports accurate diagnosis.

9. Early Warning Signs Farmers Should Not Ignore

Although metabolic disorders may initially be silent, attentive farmers can often notice subtle changes in affected animals. These may include:

- Reduced appetite
- Decreased milk yield
- Sudden weight loss
- Weakness or difficulty standing
- Nervous behaviour or muscle tremors

Recognizing these early signs and seeking veterinary advice promptly can prevent the condition from worsening.

10. Herd-Level Metabolic Profiling: A Preventive Approach

Modern dairy management is increasingly shifting from treating disease to preventing it. One important tool in this preventive approach is **herd-level metabolic profiling**. Instead of testing only sick animals, veterinarians periodically analyse blood samples from selected animals within the herd to monitor their metabolic status.

This approach allows veterinarians to evaluate key indicators such as energy balance, mineral levels, and liver function across the herd. If abnormal patterns are detected, corrective measures—such as dietary adjustments or improved mineral supplementation—can be implemented before clinical disease develops.

Herd-level metabolic profiling is particularly valuable during the transition period around calving, when animals are most vulnerable to disorders such as Milk Fever and Ketosis. By identifying metabolic stress early, farmers and veterinarians can protect animal health, maintain milk production, and prevent economic losses.

Together, veterinary pathology and metabolic profiling represent a shift toward **proactive herd health management**, where the goal is not only to treat disease but also to detect and prevent it before it affects productivity.

11. Protecting Animal Health and Farm Profitability

Metabolic disorders represent a hidden but significant challenge in modern dairy farming. While they may not spread like infectious diseases, their impact on productivity and animal welfare can be equally serious.

Understanding the causes, recognizing early signs, and adopting preventive management practices are crucial steps in protecting dairy animals. When farmers and veterinarians work together to identify and manage these invisible threats, they safeguard both animal health and the sustainability of dairy farming.

In the end, healthy animals form the foundation of a productive and profitable dairy enterprise. Recognizing the invisible dangers of metabolic disorders is the first step toward ensuring their well-being.

12. Conclusion

Metabolic disorders in dairy animals often develop quietly, without dramatic symptoms, yet their impact on animal health and farm productivity can be profound. Conditions such as Ketosis, Milk Fever, Fatty Liver Syndrome, and Grass Tetany illustrate how metabolic imbalances can undermine milk production, fertility, and overall herd health. Because these disorders often remain unnoticed in their early stages, they represent a hidden challenge for modern dairy farming.

Addressing this challenge requires a proactive approach that combines good nutrition, careful management during the transition period, and regular health monitoring. Advances in veterinary diagnostics and clinical pathology now allow veterinarians to detect metabolic imbalances early, enabling timely intervention before serious damage occurs. Ultimately, improving awareness of metabolic disorders and adopting preventive management strategies can protect animal welfare, enhance productivity, and support the long-term sustainability of dairy farms.

References:

Melendez, P., and Serrano, M. V. (2024). Update on ketosis in dairy cattle with major emphasis on subclinical ketosis and abdominal adiposity. *Veterinary Medicine and Science*, *10*(5), e1525. doi: 10.1002/vms3.1525.

Saradhi, K. P., Sandilya, A., Sravya, R. N. S., and Vijayalakshmi, P. (2024). Ketosis in dairy cattle: A comprehensive review. *International Journal of Advanced Biochemistry Research*, *8*(12), 1008-1015. DOI: 10.33545/26174693.2024.v8.i12Sm.3264

Melendez, P., and Pinedo, P. (2024). Update on fatty liver in dairy cattle with major emphasis on epidemiological patterns, pathophysiology in relationship to abdominal adiposity, and early diagnosis. *Dairy*, *5*(4), 672-687. https://doi.org/10.3390/dairy5040050

Dervishi, E., Plastow, G., Hoff, B., and Colazo, M. (2021). Common and specific mineral and metabolic features in dairy cows with clinical metritis, hypocalcaemia or ketosis. *Research in veterinary science*, *135*, 335-342. DOI: 10.1016/j.rvsc.2020.10.012

AGRICULTURE BULLETIN
ISSN: 3049-2289

Nanotechnology in Sericulture

Vaishali SP, A P SriVidhya, J Paul Mansingh*
Department of Agricultural Extension & Economics,
VIT School of Agricultural Innovations and Advanced Learning (VAIAL),
Vellore Institute of Technology, Tamil Nadu, India.

Introduction

"Silk" is the natural fibre which human found first, while earlier materials like cotton, wool, linen, and hemp were also existed. Sericulture is a Chinese word "Su (Si)" means silk and the normal English word "culture" refers to "rearing". "silkworm" the caterpillar which secretes a single thread of silk, and that is composed of a protein in the form of fluid. Silk as a unique property, because of that it is called as queen of textiles. It is compiled if lightness with warmth, sheerness with strength, and the delicacy with resilience. There are a determined structure and pattern for the silk income distribution that shows, major share of it goes to the poor farmers who rears and produces the cocoons. As per the percentage distribution, 54.6% for the cocoon producers; share for silk rears is 6.6%; the twisters receive 8.7%; weavers for12.3% and the income generated from the manufactured and sale of silk the traders take upto17.8%. Sericulture is considered as an important rural industry in India. India states 2nd place in silk production in world level after China. In India Mysore and north Bengaluru is called as "silk city" because of the silk production. India produces commercial varieties like mulberry, tsar, Eri and Muga. All over India 90% the major produced silk is mulberry silk. The only cash crop that gives quick returns to the farmers within 30days in agricultural sector is sericulture. Sericulture is an Agro-based cottage industry also called as welfare-based employment-oriented cottage industry. Problems faced in the sericulture are with the economic constraints of the price volatility, high input cost, production and technical problems, pest and disease incidence and the major one is the inadequate technology. Nanoparticles are emerged as a tool that helps in enhancing the mulberry cultivation and the silkworm production therefore nanoparticles are potentially revolutionizing the production of silk. Nanotechnology offers innovative solutions for improving productivity and sustainability in sericulture.

Fig.1. Silkworms

Basis of Nanotechnology

Nanotechnology means "technology on nanoscale" it is a branch of knowledge, with sub classification of more technology like chemistry, physics, colloidal science, biology and many other scientific fields. Nano, a Greek word 'Nanos' means dwarf, particles having the dimension less than 100 nanometre, called as nanoparticle. Example, titanium dioxide. The quantum dots are used in silk fibres for antimicrobial activity, UV protection and to enhance the mechanical strength.

ISSN: 3049-2289

Why do nanoparticles behave differently from other normal materials?

Because of its increased surface area and reactivity, large percentage of the atoms are located on the surface of the material. The main reason is surface area to volume ratio. Nano materials help in enhancing the silk fibres. The nano materials such as carbon nanotube, graphene and nano clays can reinforce the molecular level of silk with increase in its tensile strength. During the spinning process of the silk, the incorporation of the nano materials helps in the structural integrity of the silk.

Application of Nanotechnology in Mulberry Cultivation

Mulberry becomes the major food source of their Bombay's mori Silkworm, nano particles treated leaves directly influence the growth and quality of the silk and silkworm. The significant application of nanotechnology in Mulberry cultivation improved the use of Nano fertilizers which helps in efficient nutrient uptake, in traditional method of nutrient application leaching, volatilization, leads to low fertiliser use efficiency. So, Nano fertilizers help in overcoming these problems and helps in direct delivering of nutrients in a targeted manner, example: plants treated with zinc oxide nanoparticle leads to increase in shoot height, biomass, leaf area and leaf count per plants when compared with untreated plants. The core concept in use of Nano fertilizer in Mulberry cultivation is they provide controlled release of nutrients as per the availability, helps in reducing the environmental pollution and also improve the crop productivity.

Nanotechnology helps Stress tolerance in Mulberry, it frequently experienced the drought condition, degradation of soil and nutrient deficiency. The application of zinc oxide nano materials helps to improve the antioxidant enzyme and protect the plant cells from oxidative damage. Enhancement of the photosynthetic pigments, carbohydrate levels and protein synthesis are mainly done by the nanoparticles. This also helps the plan to grow even in water limited condition. The use of nanoparticles for climate resilient mulberry cultivation helps the farmers to maintain productivity under the recent climate changes.

Pest and disease are the major problems in every crop, which affects the leaf yield and quality. We can use conventional pesticide method, but which leaves harmful residue and that may also affect the health of the silkworm. The alternative side is use of nanotechnology through antimicrobial nanoparticles and nano pesticides. The nano material like silver, titanium oxide with lower chemical concentration can control plant pathogen and also reduce the spread of disease.

Nanotechnology in Silkworm health and Disease Management

The emergence of nanotechnology in recent years has become an innovative approach to improve Silkworm health, enhance immunity and manage diseases. Nano materials contain physiochemical properties such as extremely small size, high surface area and enhanced reactivity, which allows to interact efficiently with biological system of the pathogens. Study shows that nano particle can inhibit the growth

ISSN: 3049-2289

of harmful microorganism in silkworm gut, rearing environment thereby reducing morality and infection. Certain nanoparticles like gold nanoparticle are synthesised using plant extract helps in stimulation of immune mechanism in silkworm. These also enhance the defence capability of the Bombyx mori by activating the immune pathways and also by increasing their resistance against pathogens

Diseases	Management
Bacterial and viral pathogen	Silver nanoparticle (antimicrobial activity)
Bombyx mori nucleopolyhedroviral (BmNPV)	Silver nanoparticle (inhibit viral activity)

How to control viral disease?

Recent studies show nanoparticle can control this infection by virus replication and post virus interaction. During viral infection, excess lipids are being produced, which are often used by the virus for replication. This viral proliferation can be indirectly suppressing the nano silica particle and improve the survival rate in the infected population of the silkworm.

Role of Nanotechnology in improving Silk Quality

Nano particles help in improving cocoon characteristic like silk fibre strength, durability and functional properties. The significant contribution of nanotechnology in improvement of mechanical properties of silk fibres. While incorporating nanoparticles into silk during fibre formation helps in modifying the structural arrangement of silk protein. This increases tensile strength, elasticity and durability. Silk fibroin proteins are interacted with metal nanoparticles and nano composites that are responsible for the strength and elasticity of silk. The interaction results in the crystallinity of the silk fibres. Silver nano particles treated with mulberry leaves, are fed to silkworm, that shows increase in larval weight, cocoon weight, and shell ratio. These are the key indicators of the silk productivity.

Environmental and Economic benefits

The essential challenge in the sericulture today is to maintain the productivity, quality and eco-friendliness of sericulture by minimizing the use of chemicals. Although the chemical disinfectants and pesticides are widely used for the control of the silkworm and mulberry diseases, they are always harmful to the environment, mulberry trees, non-target organisms and even to the man. The nanomaterials have also been reported to possess the microbial activity. So, it can easily replace the chemical pesticides in the rearing houses. Many nanoparticles (e.g., silver nanoparticles) and chitosan-based nanomaterials have been reported to exert excellent antibacterial activity against a variety of pathogenic microorganisms that causes diseases in silkworm. Hence, their use will surely minimize the requirement of harmful chemical pesticides required for the control of diseases, thereby reducing contamination of the environment. Thus, the application of nanotechnology in sericulture will certainly improve the eco- friendliness of silk production system.

In the context of environment, green synthesis of nanoparticles is one of the emerging issues. Our recent research focuses on using plant extracts like mulberry fruit for the synthesis of eco-friendly silver nanoparticles using green nanotechnology approach. Biologically synthesized nanoparticles are non-toxic and environmentally safe as compared with chemically synthesized nanomaterials. Hence, with green nanotechnology approach, the recent developments in the area of sericulture can not only be environment friendly but also improves the productivity of the silkworms.

The fact that high quality silk fibre attracts higher price, thereby, increases the income of the silk cultivators, and thus, increases the scope of the silk commodity in the market place. By adopting

ISSN: 3049-2289

nanotechnology in sericulture, it is possible to reduce production costs, as it can reduce disease losses and enhance feed efficiency. Nanoparticles may have the capacity to utilise the nutrients present in mulberry leaves more effectively in silkworms thereby leading to growth and increased cocoon yields without any extra feeding. It may also help in reducing disease-related mortality of silkworms thereby further reducing production costs.

Conclusion

Nanotechnology is emerging as a promising innovative in sericulture. It improves silkworm health, mulberry productivity and silk quality. The use of nano particle enhances disease resistance, improve nutrient utilisation and increases cocoon yield while reducing dependence on chemical fertilizers. It also helps in minimise ecological pollution.

Reference

1. Sharma, K., & Kapoor, B. (2020). Sericulture as a profit-based industry: A review. *Indian Journal of Pure and Applied Biosciences*, 8(4), 550–562. https://doi.org/10.18782/2582-2845.8210
2. Sericulture industry in India: An overview. Retrieved from https://d1wqtxts1xzle7.cloudfront.net/55516524/6027-libre.pdf
3. Islam, T. U. (2024). The historical journey of sericulture: Insights into sustainability from past to present. *International Journal of Emerging Knowledge Studies*, 3(9). https://doi.org/10.70333/ijeks-03-09-042
4. Dukare P. G. et al., 2024. *Application of Nanotechnology for Sustainable Sericulture*: *A Review*. Journal of Advances in Biology & Biotechnology.
5. Ramanan, A., Kasivelu, G., Kamalakannan, M., Saravanan, N., & Malaichamy, K. (2025). Advancing sericulture through nanotechnology: Sustainable innovations for the future. Sustainable Materials and Technologies, 46, e01726. https://doi.org/10.1016/j.susmat.2025.e01726

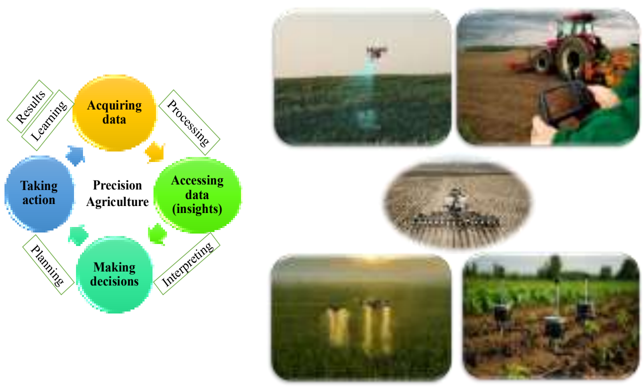
AGRICULTURE BULLETIN
ISSN: 3049-2289

Precision agriculture: An overview of techniques and future directions

Priyanka[1], Dr. Chandra Shekhar[2]
Research Scholar[1], Department of Agronomy, Dr. Khem Singh Gill Akal College of Agriculture, Eternal University, Baru Sahib, Sirmaur, HP
Assistant Professor[2], Department of Agronomy, Dr. Khem Singh Gill Akal College of Agriculture, Eternal University, Baru Sahib, Sirmaur, HP

Introduction

The word 'Precision' means exactness or accuracy. Precision Agriculture or smart farming means 'the process by which exact or accurate results of farming can be obtained'. An information and technology-based farm management system that identifies, analyses, and controls field variability by carrying out all crop production procedures in the appropriate location, at the appropriate time, and in the appropriate manner for maximum profitability, sustainability, and land resource protection. A systems approach to farming, precision agriculture maximizes the efficiency of agricultural inputs.



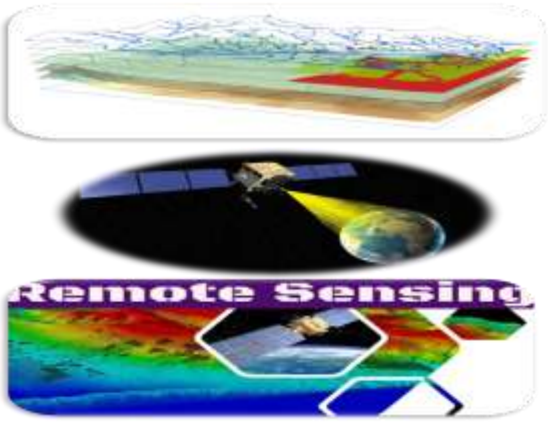
The base of precision farming is site-specific management, which recognizes that a field's soil, topography, climate, and other characteristics change. This act as the basis for the precision farming concept. Farmers may make well-informed decisions about the distribution of resources like water, seeds, pesticides, fertilizer, by accurately mapping and analysing these changes with the use of techniques like remote sensing (RS), geographic information systems (GIS), and global positioning systems (GPS), by using that crops obtain the proper quantity of water and nutrients precisely when and where they are needed, this target application of inputs maximizes the potential for development and output.

Essential elements of precision farming

1) **Data Collection:** Accurate and timely data collection about soil characteristics, crop health, weather, and other important factors is essential to precision farming. This data can be obtained through a variety of techniques, including as satellite imaging, drones, ground-based sensors, and manual sampling.
2) **Data Analysis:** Data is collected and then examined to find patterns, trends, and spatial variability in the field. To obtain useful information from the data, advanced analytics methods.
3) **Decision Support System:** Based on the analysis of decision support systems offer farmers advice and recommendations for improving farm management techniques. These systems could include of internet sites, mobile apps, and software tools that combine data from various sources and offer real-time monitoring and assistance with decision-making.
4) **Precision Application Technology:** Precision farming applies inputs (which include water, fertilizers, and pesticides) precisely and only where necessary using cutting-edge technologies. It consists of devices such as data systems, sensors,

ISSN: 3049-2289

automatic irrigation, variable rate equipment, and GPS- guided machinery. Farmers can control field variability and modify inputs for certain regions or even individual animals by utilizing computer science, electronics, and geoprocessing. This increases productivity, decreases waste, and enhances efficiency.



Precision farming is necessary

1. To evaluate and control field variability
2. For acting appropriately at the appropriate moment and location
3. For higher productivity
4. To increasing the efficiency of inputs
5. To make the most of the least amount of land

Components of Precision Agriculture

1) **Global Positioning Systems:** GPS is a satellite-based navigation system that allows users to determine their exact location (latitude, longitude, and altitude) anywhere on Earth, at any time, in any weather conditions.
2) **Geographic Information Systems:** GIS is a computer-based system used to collect, store, analyze, manage, and visualize spatial (geographic) data.
3) **Variable Rate Technology:** VRT is a farming method that allows inputs like fertilizer, seeds, pesticides, and water to be applied at different rates across a field, instead of applying the same amount everywhere.
4) **Remote Sensing:** Remote sensing is the process provide the data, collecting information about crops or land without physically touching them, typically using satellites, drones, or aircraft.
5) **Yield Monitors:** Yield monitors are devices installed on harvesting machines that measure and record crop yield and moisture content as the crop is harvested.

Future Prospects

Precision agriculture's future possibilities are focused on cutting-edge technology that improve farming's sustainability, productivity, and efficiency. While enhanced remote sensing and Internet of things-based smart sensors will enable real-time monitoring of the soil, crops, and weather conditions, innovations like artificial intelligence and machine learning will enable smarter decision-making by forecasting crops performance, pest outbreak, and optimal input use. Data-driven systems will improve water and nutrient management lessen environment effect, while autonomous machinery and robotics are anticipated to decrease labour dependency and improve operational precision. Furthermore, cloud-based farm management platform, blockchain-based traceability, and precision livestock husbandry will improve market access, food security, and transparency.

Overall, all things considered, precision agriculture has the potential to revolutionize conventional farming into a highly effective, technologically advanced, climate-smart system that can sustainably meet the world's expanding food need.

AGRICULTURE BULLETIN
ISSN: 3049-2289

Carbon Sequestration through Biodiversity Restoration

Vidushi. K[1]*, Arvind Kumar Shukla[2], Anil Kumar[3]
[1]Post Graduate Research Scholar, Department of Horticulture, Malla Reddy University Hyderabad- 500100
[2]Ph.D. Scholar, Department of Soil Science and Agricultural Chemistry, Banda University of Agriculture and Technology Banda, Uttar Pradesh
[3]Assistant Professor, Department of Agronomy, School of Agriculture, Eklavya University Damoh, Madhva Pradesh-470661

1. Introduction

Climate change is one of the most pressing global challenges of the 21st century, driven largely by the rising concentration of greenhouse gases such as carbon dioxide (CO_2) in the atmosphere. This increase has led to global warming, altered weather patterns, and environmental degradation. Carbon sequestration, the process of capturing and storing atmospheric CO_2, has emerged as an effective strategy to mitigate climate change impacts. Among various approaches, biodiversity restoration offers a sustainable and nature-based solution. It involves the recovery of degraded ecosystems through the reintroduction of native species, improvement of ecological processes, and strengthening ecosystem resilience. Restored ecosystems function as efficient carbon sinks, absorbing CO_2 via photosynthesis and storing it in plant biomass and soil organic matter, thereby contributing significantly to climate change mitigation and ecological balance.

2. Concept of Carbon Sequestration

Carbon sequestration refers to the long-term capture and storage of carbon in natural and artificial reservoirs such as plants, soils, oceans, and geological formations. It plays a vital role in reducing atmospheric carbon dioxide (CO_2) levels and mitigating climate change. This process occurs through two primary pathways: biological and geological sequestration.

2.1 Biological Carbon Sequestration

Biological carbon sequestration occurs mainly through photosynthesis, where plants absorb CO_2 from the atmosphere and convert it into organic matter. The captured carbon is stored in different components, including plant biomass such as leaves, stems, and roots, as well as in soil organic matter formed through the decomposition of plant residues. This pathway is closely linked to biodiversity and ecosystem restoration.

2.2 Geological Carbon Sequestration

Geological carbon sequestration involves capturing CO_2 and storing it deep underground in rock formations, depleted oil and gas reservoirs, or saline aquifers. Although effective, it is more technological and less connected to ecological restoration processes.

2.3 Carbon Pools

Carbon is stored in various pools, including aboveground biomass (trees and shrubs), belowground biomass (roots), soil organic carbon (SOC), and dead organic matter such as litter and woody debris, which together contribute to long-term carbon storage.

ISSN: 3049-2289

Source: https://mahabal.com/

3. Biodiversity Restoration: Definition and Scope

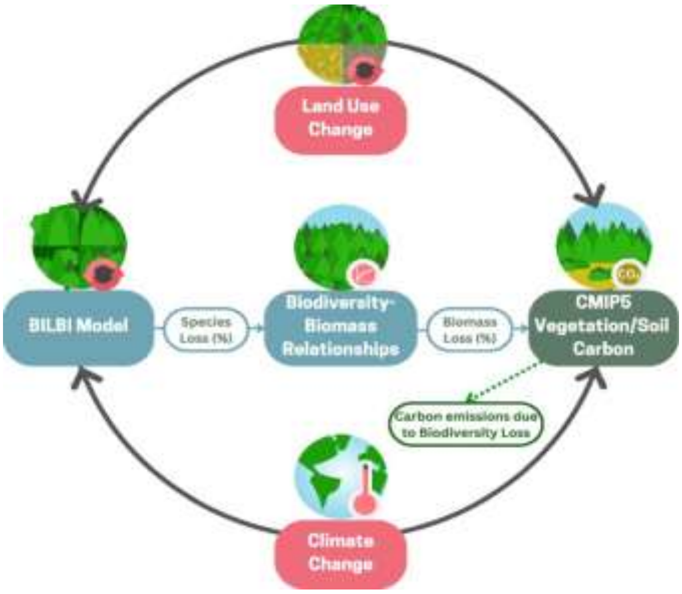
Biodiversity restoration is the process of assisting the recovery of ecosystems that have been degraded, damaged, or destroyed due to natural or human-induced disturbances such as deforestation, overgrazing, pollution, and climate change. It aims to re-establish the structure, function, and diversity of ecosystems so that they can sustain ecological balance and provide essential ecosystem services. Biodiversity restoration is a key component of sustainable environmental management and plays a significant role in enhancing carbon sequestration and climate resilience.

The scope of biodiversity restoration is broad and includes multiple ecological and management practices. One of its primary focuses is the re-establishment of native plant species, which are well adapted to local environmental conditions and support native wildlife. Restoring soil health is another critical aspect, involving the improvement of soil structure, nutrient content, and microbial activity. Healthy soils enhance plant growth and increase the capacity to store carbon.

Additionally, biodiversity restoration seeks to revive ecological interactions such as pollination, nutrient cycling, and predator-prey relationships, which are essential for maintaining ecosystem stability. Enhancing ecosystem services is also a major objective, including improved water regulation, soil fertility, climate regulation, and biodiversity conservation.

Types of Restoration

1. Ecological Restoration – This involves the complete recovery of an ecosystem to its original state, including its species composition, structure, and ecological functions. It aims to recreate a self-sustaining and resilient ecosystem.
2. Rehabilitation – This focuses on the partial recovery of ecosystem functions and productivity without necessarily restoring the original biodiversity or structure. It is often applied where full restoration is not feasible.
3. Reclamation – This involves improving the usability of severely degraded lands, such as mined areas or wastelands, making them suitable for agriculture, forestry, or other purposes.



Source: https://www.nature.com/

4. Link between Biodiversity and Carbon Sequestration

Biodiversity plays a crucial role in enhancing carbon sequestration by improving ecosystem productivity, stability, and resilience. Diverse ecosystems are generally more efficient at capturing and storing carbon compared to monocultures, as they utilize resources more effectively and maintain ecological balance over time. The relationship between biodiversity and carbon sequestration is driven by several key mechanisms:

4.1 Increased Biomass Production

- Diverse plant communities tend to produce greater overall biomass due to varied growth patterns and resource use.
- Higher biomass accumulation leads to increased carbon storage in plant tissues such as leaves, stems, and roots.

4.2 Improved Soil Carbon Storage

- A variety of plant species contributes to diverse root structures, which enhance soil organic matter through root exudates and decomposition.
- Greater microbial diversity in biodiverse soils improves the breakdown and stabilization of organic matter, leading to long-term carbon storage in soils.

4.3 Enhanced Ecosystem Stability

- Biodiverse ecosystems are more resilient to environmental stresses such as droughts, pests, and diseases.
- This stability ensures continuous carbon uptake and reduces the risk of carbon loss due to disturbances, allowing carbon to remain stored for longer periods.

4.4 Complementarity Effect

- Different species utilize sunlight, water, and nutrients in complementary ways, reducing competition and increasing overall efficiency.
- This efficient resource utilization enhances productivity and leads to greater carbon capture and sequestration at the ecosystem level.

5. Mechanisms of Carbon Sequestration in Restored Ecosystems

Restored ecosystems play a vital role in capturing and storing atmospheric carbon through various biological and ecological processes. These mechanisms operate at both plant and soil levels, ensuring both short-term and long-term carbon storage.

5.1 Photosynthesis

Photosynthesis is the primary mechanism of carbon sequestration in ecosystems. Green plants absorb carbon dioxide (CO_2) from the atmosphere and convert it into organic compounds using sunlight and water:

$$CO_2 + H_2O \rightarrow C_6H_{12}O_6 + O_2$$

The carbon fixed during this process becomes part of plant biomass, including leaves, stems, and roots, forming the foundation of carbon storage in terrestrial ecosystems.

5.2 Soil Carbon Formation

A significant portion of captured carbon enters the soil through plant litter, fallen leaves, and dead roots. These organic materials decompose over time and are transformed into soil organic carbon (SOC). This process enhances soil fertility and creates a stable carbon pool that can persist for long periods, especially in well-managed restored ecosystems.

5.3 Root Carbon Deposition

Deep-rooted plant species play an important role in transferring carbon into deeper soil layers. Roots release organic compounds and, upon decay, contribute to carbon accumulation below the surface. Carbon stored in deeper soil layers is less susceptible to disturbance, thereby increasing long-term sequestration potential.

5.4 Microbial Activity

Soil microorganisms, including bacteria and fungi, decompose organic matter and convert it into humus—a stable form of organic carbon. This

ISSN: 3049-2289

microbial transformation helps in stabilizing carbon in soils for decades or even centuries, making it a critical component of long-term carbon sequestration.

6. Ecosystems and Their Role in Carbon Sequestration

Different ecosystems play distinct and significant roles in carbon sequestration due to their unique structures, functions, and biological processes. Restoring and managing these ecosystems effectively can greatly enhance their capacity to capture and store atmospheric carbon dioxide (CO_2).

6.1 Forest Ecosystems

- Forests are among the largest global carbon sinks, storing carbon in trees, understory vegetation, and soils.
- Tropical forests, in particular, have high biomass density and sequester substantial amounts of carbon.
- Practices such as afforestation (planting new forests) and reforestation (restoring degraded forests) significantly increase carbon stocks and improve ecological balance.

6.2 Grasslands

- Grasslands store a major portion of their carbon below ground in the form of soil organic carbon.
- The extensive and deep root systems of grasses contribute to carbon accumulation in soil layers, making them resilient carbon reservoirs even under grazing conditions.

6.3 Wetlands and Peatlands

- Wetlands and peatlands are highly efficient carbon storage systems due to their waterlogged conditions, which slow down decomposition.
- These ecosystems store carbon in saturated soils for long periods, often over centuries, making them critical for long-term carbon sequestration.

6.4 Agroecosystems

- Agroecosystems, especially agroforestry systems, integrate trees with crops and sometimes livestock.
- This integration enhances biodiversity, improves soil health, and increases carbon storage in both biomass and soil.

6.5 Coastal Ecosystems (Blue Carbon)

- Coastal ecosystems such as mangroves, seagrasses, and salt marshes are known as blue carbon ecosystems.
- They sequester and store carbon at rates often higher than terrestrial ecosystems, particularly in their sediments, contributing significantly to climate change mitigation.

7. Role of Biodiversity Restoration in Climate Change Mitigation

Biodiversity restoration plays a crucial role in mitigating climate change by strengthening natural systems that capture, store, and regulate carbon. Restored ecosystems enhance ecological balance and increase the efficiency of carbon sequestration processes, making them an important nature-based solution for addressing global warming.

7.1 Carbon Sink Enhancement

Restored ecosystems such as forests, grasslands, and wetlands act as effective carbon sinks by absorbing more atmospheric CO_2 through photosynthesis. Increased vegetation cover leads to higher biomass production, which stores carbon in plant tissues and soil, thereby reducing the concentration of greenhouse gases in the atmosphere.

7.2 Reduced Greenhouse Gas Emissions

Healthy ecosystems, particularly soils rich in organic matter, help in reducing emissions of harmful greenhouse gases like methane (CH_4) and nitrous oxide (N_2O). Improved soil structure and microbial activity enhance nutrient cycling and minimize carbon losses, contributing to a more stable climate system.

7.3 Climate Regulation

Vegetation plays an important role in regulating local and regional climates. Through processes like transpiration and shading, plants help in maintaining temperature balance, increasing humidity, and influencing rainfall patterns. This contributes to stabilizing climatic conditions and reducing extreme weather events.

7.4 Disaster Risk Reduction

Restored ecosystems act as natural buffers against environmental hazards. Forests reduce soil erosion and landslides, wetlands absorb excess floodwater, and vegetation cover helps in conserving soil moisture during droughts. Thus, biodiversity restoration reduces the severity and impact of natural disasters.

8. Restoration Strategies for Carbon Sequestration

Restoration strategies play a vital role in enhancing carbon sequestration while improving ecosystem health and productivity. Afforestation and reforestation involve planting trees on degraded or deforested lands, which helps restore forest ecosystems and increases carbon storage in biomass and soils. The use of native species ensures better adaptability and long-term ecological stability. Agroforestry systems integrate trees with crops and livestock, promoting biodiversity and enhancing carbon storage while also improving farm productivity and resilience. Soil restoration practices such as conservation tillage, cover cropping, and the application of organic amendments like compost and biochar significantly improve soil organic carbon and fertility. Wetland restoration, including rewetting drained areas and protecting peatlands, helps maintain their high carbon storage capacity. Similarly, effective grassland management through controlled grazing and reseeding of native grasses enhances vegetation cover and increases soil carbon sequestration.

9. Factors Affecting Carbon Sequestration

Carbon sequestration is influenced by several environmental and management-related factors that determine the capacity of ecosystems to capture and store carbon effectively. Understanding these factors is essential for improving carbon storage and developing sustainable land-use strategies.

9.1 Climate

Climate plays a significant role in carbon sequestration. Temperature and rainfall directly affect plant growth, photosynthesis, and decomposition rates. Warm and moist conditions generally enhance plant productivity and carbon uptake, whereas extreme temperatures and low rainfall can limit biomass production and reduce carbon storage potential.

9.2 Soil Type

Soil characteristics greatly influence carbon storage. Clay-rich soils have a higher capacity to retain organic carbon due to their fine texture and ability to protect organic matter from decomposition. In contrast, sandy soils have lower carbon retention capacity because of poor structure and rapid drainage.

9.3 Vegetation Type

Different types of vegetation vary in their carbon sequestration potential. Forest ecosystems store large amounts of carbon in biomass, while grasslands store more carbon in soils through their extensive root systems. The type and diversity of vegetation significantly determine overall carbon storage.

9.4 Management Practices

Sustainable land management practices such as conservation tillage, afforestation, and organic farming enhance carbon sequestration. Conversely,

ISSN: 3049-2289

poor practices like deforestation and overgrazing lead to carbon loss and environmental degradation.

10. Measurement and Monitoring of Carbon Sequestration

Accurate measurement and monitoring of carbon sequestration are essential for evaluating the effectiveness of restoration efforts and understanding carbon dynamics in ecosystems. Various scientific methods and tools are used to assess carbon storage in biomass and soil.

10.1 Field Measurements

Field-based methods involve direct assessment of carbon stocks. Biomass estimation is carried out by measuring tree height, diameter, and density to calculate aboveground and belowground carbon. Soil sampling is used to determine soil organic carbon (SOC) content at different depths, providing insights into long-term carbon storage.

10.2 Remote Sensing

Remote sensing techniques use satellite imagery and aerial data to monitor vegetation cover, land-use changes, and ecosystem health over large areas. These methods are cost-effective and enable continuous observation of carbon sequestration trends at regional and global scales.

10.3 Carbon Models

Carbon models are computational tools used to simulate and predict carbon storage and fluxes over time. They integrate data on climate, soil, vegetation, and management practices to estimate future carbon sequestration potential under different scenarios.

10.4 Indicators

Key indicators such as soil organic carbon (SOC), vegetation cover, and biodiversity indices are used to evaluate ecosystem health and carbon sequestration capacity, helping in effective monitoring and decision-making.

11. Challenges in Biodiversity Restoration for Carbon Sequestration

Biodiversity restoration for carbon sequestration faces several challenges that can limit its effectiveness and long-term success. Land degradation and deforestation remain major issues, as they reduce vegetation cover and soil carbon stocks, making restoration more difficult. Climate variability, including irregular rainfall and extreme temperatures, further affects plant growth and ecosystem recovery. Invasive species pose another significant threat by outcompeting native species and disrupting ecological balance. Additionally, lack of adequate funding and weak policy support hinder large-scale restoration initiatives. Limited community participation and awareness also reduce the sustainability of restoration programs.

12. Opportunities and Benefits

Despite the challenges associated with biodiversity restoration, it offers numerous environmental, economic, and social benefits that contribute to sustainable development and climate resilience.

12.1 Environmental Benefits

Biodiversity restoration plays a significant role in climate change mitigation by enhancing carbon sequestration in vegetation and soils. It improves soil fertility through better nutrient cycling and increased organic matter content. Additionally, restored ecosystems help in water conservation by improving infiltration, reducing runoff, and maintaining hydrological balance. These benefits collectively support ecosystem stability and environmental sustainability.

12.2 Economic Benefits

From an economic perspective, biodiversity restoration creates opportunities through carbon credits and participation in carbon markets, providing additional income sources. It also enhances agricultural productivity by improving soil health

ISSN: 3049-2289

and ecosystem services, leading to increased and sustainable farm income over the long term.

12.3 Social Benefits

Socially, biodiversity restoration generates employment and livelihood opportunities, particularly in rural areas through activities such as afforestation and land management. It contributes to food security by promoting sustainable agricultural practices. Furthermore, it strengthens community resilience by reducing vulnerability to climate change and environmental risks, ensuring a more stable and secure future.

15. Conclusion

Carbon sequestration through biodiversity restoration is a sustainable, cost-effective, and nature-based solution to combat climate change. Restoring ecosystems not only enhances carbon storage but also improves biodiversity, soil health, and ecosystem resilience. For long-term success, integrated approaches involving science, policy, and community participation are essential.

References

De Deyn, G. B., Shiel, R. S., Ostle, N. J., McNamara, N. P., Oakley, S., Young, I., ... & Bardgett, R. D. (2011). Additional carbon sequestration benefits of grassland diversity restoration. *Journal of Applied Ecology*, *48*(3), 600-608.

Di Sacco, A., Hardwick, K. A., Blakesley, D., Brancalion, P. H., Breman, E., Cecilio Rebola, L., ... & Antonelli, A. (2021). Ten golden rules for reforestation to optimize carbon sequestration, biodiversity recovery and livelihood benefits. *Global Change Biology*, *27*(7), 1328-1348.

Edwards, D. P., & Cerullo, G. R. (2024). Biodiversity is central for restoration. *Current Biology*, *34*(9), R371-R379.

Wheeler, C. E., Omeja, P. A., Chapman, C. A., Glipin, M., Tumwesigye, C., & Lewis, S. L. (2016). Carbon sequestration and biodiversity following 18 years of active tropical forest restoration. *Forest ecology and management*, *373*, 44-55.

Yang, Y., Tilman, D., Furey, G., & Lehman, C. (2019). Soil carbon sequestration accelerated by restoration of grassland biodiversity. *Nature communications*, *10*(1), 718.

ISSN: 3049-2289

Impact of Heat Sensitivity on Crop Performance and Productivity

H V S Shekhawat, J K Sharma and V K Meena
Agriculture University-Jodhpur

Heat stress is a major abiotic factor limiting agricultural productivity worldwide. Rising global temperatures have intensified the frequency and severity of heat episodes, adversely affecting crop growth, development, and yield. This article examines the physiological, biochemical, and agronomic impacts of heat sensitivity on crops, with emphasis on reproductive failure, metabolic disruption, and yield reduction, along with adaptive strategies for mitigation.

1. Introduction

Temperature is a critical environmental determinant of plant growth and development. Each crop species has an optimal temperature range, beyond which physiological processes are disrupted. Heat sensitivity refers to the susceptibility of plants to elevated temperatures that exceed their threshold limits, leading to stress responses that impair productivity. With ongoing climate change, heat stress has emerged as a significant threat to global food security.

2. Effects on Growth and Development

High temperature stress affects multiple stages of plant development:

- **Seed Germination:** Elevated temperatures can inhibit enzymatic activity required for germination, resulting in reduced and uneven seedling emergence.
- **Vegetative Growth:** Accelerated phenological development shortens the growth duration, limiting biomass accumulation.
- **Root System Impairment:** Heat stress reduces root elongation and functionality, thereby decreasing water and nutrient uptake efficiency.

3. Reproductive Sensitivity to Heat Stress

The reproductive phase is the most heat-sensitive stage in crops.

- **Pollen Viability and Sterility:** High temperatures disrupt microsporogenesis, leading to pollen sterility.
- **Floral Abortion:** Heat stress induces flower drop and reduces successful fertilization.
- **Grain and Fruit Set Reduction:** Poor fertilization results in decreased seed set and fruit formation.

Short-term exposure to high temperatures during flowering can cause irreversible yield losses in crops such as wheat and rice.

4. Physiological and Biochemical Responses

4.1 Photosynthesis and Respiration

Heat stress negatively affects photosynthetic efficiency by damaging chloroplast structures and inhibiting key enzymes such as Rubisco. Concurrently, respiration rates increase, leading to higher energy consumption and reduced net carbon gain.

4.2 Water Relations

Elevated temperatures increase evapotranspiration rates, resulting in rapid depletion of soil moisture and plant water deficits. This condition exacerbates drought stress and leads to stomatal closure, further limiting photosynthesis.

ISSN: 3049-2289

4.3 Cellular Damage and Oxidative Stress

Heat stress causes protein denaturation, enzyme inactivation, and destabilization of cellular membranes. It also leads to the accumulation of reactive oxygen species (ROS), which damage lipids, proteins, and nucleic acids.

5. Impact on Yield and Quality

Heat sensitivity significantly affects both the quantity and quality of crop produce:

- Reduced Yield Components: Decrease in grain number, grain size, and weight.
- Nutritional Quality Decline: Lower protein and starch accumulation.
- Fruit Quality Degradation: Increased incidence of sunburn, reduced sugar content, and poor texture.

6. Agronomic and Ecological Implications

Heat stress influences agricultural systems at a broader scale:

- Shifts in Cropping Patterns: Alteration in suitable agro-climatic zones.
- Increased Pest and Disease Pressure: Warmer conditions favor pest proliferation.
- Threat to Food Security: Reduced productivity in heat-prone regions, particularly in tropical and semi-arid areas.

7. Adaptation and Mitigation Strategies

7.1 Genetic Approaches

- Development of heat-tolerant cultivars through conventional breeding and molecular techniques.
- Utilization of heat shock proteins and stress-responsive genes.

7.2 Agronomic Practices

- Adjustment of sowing dates to avoid peak heat periods.
- Adoption of efficient irrigation methods such as drip irrigation.
- Use of mulching to conserve soil moisture.

7.3 Crop Management Techniques

- Application of anti-transpirants and growth regulators.
- Implementation of agroforestry systems to provide shading and microclimate regulation.

8. Conclusion

Heat sensitivity poses a critical challenge to sustainable crop production under changing climatic conditions. Its impact spans from cellular damage to large-scale yield reductions. Integrated approaches combining genetic improvement and agronomic management are essential to enhance crop resilience and ensure food security in the face of global warming.

AGRICULTURE BULLETIN
ISSN: 3049-2289

Weberian Ossicles: A Unique Auditory Adaptation in Freshwater Teleost Fishes

Amit Singh Kshatri[1*], Shikha Ahalavat[2], Aditya Kumar Upadhyay[1]
[1]College of Fisheries Science, CCS Haryana Agricultural University Hisar (125004), Haryana, India
[2]College of Basic Sciences and Humanities, CCS Haryana Agricultural University Hisar (125004), Haryana, India

Introduction

Weberian ossicles, a unique anatomical characteristic of ostariophysan fishes, comprise a particular chain of tiny bony components that join the internal ear (membranous labyrinth) and swim bladder. Ernst Heinrich Weber first identified this special auditory connection in 1820. It improves sound perception by sending swim bladder vibrations to the inner ear. The fishes with Weberian ossicles, which are mostly present in important freshwater fish groups like cyprinids, silurids, characids and gymnotids, are referred to as Ostariophysi.

1. Structure of Weberian Ossicles

The four ossicles that make up the Weberian apparatus, the claustrum, scaphium, intercalarium and tripus are joined by ligaments to form a functional chain that connects the inner ear, swim bladder and vertebral column.

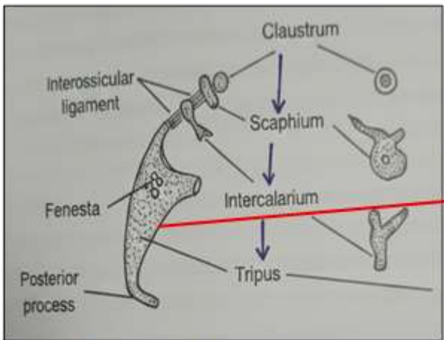


Fig: Weberian ossicles of teleost

(Source: Khanna & Singh, 2016)

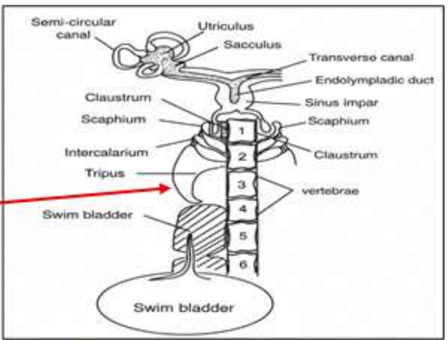


Fig: Diagrammatic representation of the connection of Swim bladder with ear through Weberian ossicles.

The claustrum, which articulates with or forms a portion of the neural arch of the first vertebra, is the smallest and most anterior ossicle among these (Duclos & Grande, 2025). In cyprinids, the intercalarium is shaped like a rod and is joined to the centrum of the second vertebra by an interossicular ligament that connects it to the scaphium. The largest ossicle is the tripus, which is usually triangular in shape. Its posterior process called the transformator, connects directly to the swim bladder wall, facilitating effective sound vibration transmission, while its middle process articulates with the vertebral column between the second and third vertebrae.

2. Origin, Homology and Connection with the Membranous Labyrinth

The function of the Weberian ossicles is similar to that of the mammalian ear ossicles but their evolutionary origins are different. The Weberian ossicles are mostly derived from modified segments of the first three vertebrae (Popper *et al.*, 2022). There is a general agreement that the Weberian apparatus is derived from the vertebrae, even though various authors have offered differing interpretations about the exact vertebral components involved. The semicircular canals, utriculus and sacculus that make up the membrane labyrinth of the internal ear are connected to the swim bladder by these ossicles, which serve as a vital functional link. Sound vibrations follow a defined transmission pathway from the swim bladder, Weberian ossicles to the sinus impar, sinus endolymphaticus, transverse canal, sacculus and finally the internal ear are the specific site along which sound waves travel to enhance auditory sensitivity in ostariophysan fish.

ISSN: 3049-2289

3. Mechanism and Working of Weberian Ossicles

There are actually two main ways that the Weberian ossicles transfer sound waves to the internal ear: directly as in siluroid fish, and indirectly as in cyprinids fish with a large, well-developed swim bladder. The swim bladder in cyprinids responds to changes in water pressure by expanding and contracting in reaction to sound waves. This mechanical movement is transmitted successively through the tripus and scaphium, the perilymph and the sacculus of the inner ear. In contrast to mammals, which primarily use the impact of their ossicles to transmit sound, ostariophysan fishes use pressure and tension changes for auditory transmission, which makes it possible to perceive low-frequency sounds in aquatic environments.

4. Functions of Weberian Ossicles

In ostariophysan fish, the Weberian ossicles serve a number of important functions, primary among them being the **perception of sound** and the control of pressure. Compared to non-ostariophysan fishes, these fishes are able to detect higher sound frequencies and lower sound intensities due to the efficient transmission of sound vibrations from the swim bladder to the inner ear; experimental removal of the ossicles results in a significant decrease in hearing efficiency. The ossicles serve a **hydrostatic function** in addition to hearing, allowing fishes to precisely regulate buoyancy by detecting variations in swim bladder volume at various depths. They may also have a **barometric role**, serving as a pressure-sensitive system that enables fish to sense differences in atmospheric pressure. Some species like loaches, are especially sensitive to these changes.

5. Conclusion

In ostariophysan fish, the Weberian ossicles are a unique auditory adaption that significantly improves sound perception by creating a mechanical connection between the swim bladder and the membrane labyrinth. This structure, which is mostly derived from the anterior vertebrae and is not similar with mammalian ear ossicles, shows an independent evolutionary answer for fishes to have better hearing. The claustrum, scaphium, intercalarium and tripus function together to efficiently transmit pressure-induced vibrations from the swim bladder to the inner ear, enabling the detection of lower sound intensities and higher frequencies. Weberian ossicles play a multifunctional role in the ecological success of ostariophysan fishes, since they contribute to hydrostatic sensitivity and may help detect changes in external pressure in addition to their primary auditory function.

6. References

Duclos, K. K., & Grande, T. C. (2025). Siluriform Weberian Apparatus. *Catfishes, a Highly Diversified Group: Volume 1: Their Outstanding Biology*, 1715.

Khanna, S. S., & Singh, H. R. (2016). *A textbook of fish biology and fisheries*. Narendra Publishing House.

Popper, A. N., Hawkins, A. D., & Sisneros, J. A. (2022). Fish hearing "specialization"–a re-evaluation. *Hearing research*, *425*, 108393.

AGRICULTURE BULLETIN

ISSN: 3049-2289

Cultivation Practices of Tuberose Under Marginal Conditions: A Case Study of a Marginal Farmer from Chengalpattu District, Tamil Nadu

Devisri M B, Nirosha R, A P SriVidhya, J Paul Mansingh*

Department of Agricultural Extension & Economics,

VIT School of Agricultural Innovations and Advanced Learning (VAIAL),

Vellore Institute of Technology, Tamil Nadu, India

Introduction

Polianthes tuberosa is a flower known for its fragrance, beautiful vibrant white flowers that has high demand in garland making, perfumery, cosmetics, essential oil extraction and bouquets. it is an important commercial loose flower widely cultivated in Tamil Nadu which holds second rank in its production in India. Farmers cultivate tuberose due to its Hardy nature, adaptability to various soil types, low maintenance requirements compared to other commercial flowers. tuberose provides steady income to farmers as it has a long flowering period and continuous yield.

The aim of the study was to document the process that was followed by the farmer from cultivation to marketing. A Field visit was made to observe the cultivation practices of tuberose by the farmer in Chengalpattu district. During the visit, a personal interview was conducted with a local tuberose farmer who shared about the cultivation practices and challenges involved in tuberose farming.

Figure 1. Tuberose cultivated field at Kadappari, Tamil Nadu

Methodology

The Field visit was conducted on 1 March 2026 at Kadappari village in Chengalpattu district of Tamil Nadu to gather information about tuberose cultivation (Figure 1). Data were collected through a structured personal interview with the farmer, Mr. Sankaran K, who is the resident of Irandadi village, Perumbairkandigai, Tamil Nadu, 603310 (Figure 2, Table 1). Along with the interview, direct field observation was done to understand the cultivation practices, farm conditions, and crop management techniques. The information collected from the farmer and the observations made in the field were used to prepare this article.

Table 1. Farmer profile

Name of the farmer	Sankaran. K
Age	47
Field Location	Kadappari Village, Cheyyur Taluk, Chithamur Block, Chengalpattu District, Tamil Nadu – 603310.
Education qualification	B.com graduate
Farming Experience	25 years
Land Holdings	1.5 acres out of which 33 cents were under Tuberose cultivation

ISSN: 3049-2289

Figure 2. Tuberose cultivation farmer

Land preparation and planting practices

Sandy soil is available in the field with proper nutrient management like FYM applications. Farmer usually follow three steps while preparing the land

- Primary tillage: use plough to loosen the soil
- Pre irrigation: Irrigate the field completely before the secondary tillage operation this ensures the moisture level of the field
- Secondary tillage: Finally, a rotavator is used to level the land.

During Aadi pattam (mid-July to mid-August), the cultivation of tuberose is carried out and also Aadi pattam is considered as suitable for tuberose bulbs. Medium- sized hybrid bulbs were used as planting material which ensures optimum flowering potential. The bulbs are planted at the depth of 2-3 inches (5-7.5cm) with a spacing of approximately 6 inches between the Tuberose plants. The farmer procures the tuberose bulbs from other known farmers. For current cultivation about four gunny bags of bulbs (40 kg of bulbs per gunny bag) were purchased. Price of one gunny bag of bulb is ₹1000, In total, around 160 kgs of bulbs were used for cultivating tuberose with an estimated cost of ₹4000 for planting material.

Crop management practices

The farmer follows certain cultivation techniques to ensure proper health and productivity of tuberose.

- **Irrigation:** During hot summer months the crop is irrigated with the gap interval of 4-5 days. While, in the case of winter or cloudy conditions, irrigation is provided for every 10 days gap interval to meet the water requirements of the crop.
- **Nutrient Management:** The farmer starts fertilizer application, after two months of planting. He uses DAP and complex fertilizers (15 kg each, totalling 25 kg) applied at intervals of 15-20 days as per the crop nutrient requirements.
- **Weed management:** No severe weed infestation was observed in the field. If any weeds appear that are removed manually by hand weeding method, almost done once in every 15 days (Figure 3).

Figure 3. Weeding in the Tuberose field

- **Pest and disease management:** Bud borer and Mealy bug were the major pest that arises in the field. And also, the farmer mentioned that the occurrence of flower blemish in some tuberose flowers, which damages the flower quality and appearance. These are controlled through the application of insecticides and fungicides such as Acephate + Imidacloprid for Mealy bug, 505 + Emamectin benzoate for Bud borer and for flower blemishes

ISSN: 3049-2289

Matalaxyl + Mancozeb is applied as per the recommended dose and intervals. According to the farmer's opinion these measures helps to reduce pest and disease infestation in his tuberose field.

Harvesting and yield

In tuberose cultivation, the flowering begins typically six months after planting and continues to produce flowers for up to 3 years (Figure 4). Harvesting is usually carried out daily (early morning hours). Sometimes it may vary according to flowering intensity. During favourable conditions farmer reported that yield may reach in the range 15-25 kg, whereas during unfavourable conditions like heavy rainfall, the yield decreases to 1-1.5kg. Without any damage flowers are carefully harvested using hand-picking and prepared for marketing. According to the farmer's perspective the quantity of flowers yield depends heavily on both the climatic conditions and crop management practices.

Figure 4. Pre-flowering stage of Tuberose

Marketing and price of tuberose flowers

After harvest Tuberoses were carefully packed by ensuring freshness and taken to the Tindivanam flower market, which acts as the main marketing centre for the farmer to sell his produce. The flowers that are cultivated by the different farmers in the village are collectively loaded together and sent to the market, The transportation charge is ₹10 per kg of flowers. The selling price of tuberose differs based on market demand and festival occasions. Under the normal market situation, the price ranges between ₹350 to ₹400 per kg. However, during festivals the demand for flowers was relatively increased up to ₹600 per kg. The farmer also describes fluctuations of price that impact the revenue. Despite these fluctuations, tuberose cultivation remains profitable due to its long yielding nature.

Problems faced by the farmer

During the interaction, the farmer shared about various challenges involved in tuberose production. Labour shortage is the one of the main issues faced by the tuberose cultivators especially during weeding. The farmer also mentioned that heavy rainfall and water stagnation can affect flower yield. Moreover, due to market price fluctuations that change according to the surrounding conditions, there is no fixed income for the farmers to run their life.

Farmer's opinion and suggestions for new tuberose cultivator

As per the farmer's point of view tuberose cultivation can be profitable and generate staple income only if proper management practices are followed. Even though an adverse weather condition that affects the yield it can be control by proper planning and timely field management. In spite of these challenges, Farmer also emphasized that farming is subjected to unpredictable factors beyond the farmer's control. Though risks are hard to entirely manage but it can be minimized. Based, on his experience, he shared some important suggestions for new tuberose cultivators. Before planting tuberose bulbs Adequate amount of Farmyard manure should be applied. After applying manure, tillage operation should be carried out for making field suitable for cultivation then follow up with irrigation so if there any weed seed present in the soil or manure it will germinate. once weeds emerge do hand weeding thus, it reduces the pressure over weed management for initial days and make field fit for tuberose cultivation. At last, he

ISSN: 3049-2289

encourages other farmers to consider cultivating tuberose as a means to obtain better returns.

Personal Observation

Figure 5. Tuberose farmer's wife Maariyammal

During the visit, I noticed that the flower yield was relatively low but proper management practices were taken. While enquiring about this to the farmer, he said that it was mainly due to heavy rainfall during the past few months. Moreover, water stagnation had also occurred, since the field is located in a low-lying area. So, due to these reasons, the flower production had reduced significantly at present. Even though the yield was reduced, the plants appeared healthy and were free from major pests, diseases, and weeds. Along with tuberose, he also cultivates some other crops like paddy, chilli, radish, and brinjal. He also owns cows and poultry, although the cows are maintained in the farm itself for farmyard manure production. Farming activities are primarily carried out by the farmer and his family members; however, for weeding, additional labourers are hired. And particularly, the farmer mentioned that his wife plays an important role in supporting and developing the farming activities (Figure 5).

Conclusion

Overall, the field visit provided the practical experience about tuberose cultivation and the farmer's lifestyle associated with it. From this study, we can understand that, though there are many constraints in tuberose cultivation, it acts as a stable and promising income for small and marginal farmers with minimal management practices. Therefore, with proper care, management and good marketing facilities, tuberose can play a role as assured income crop for small and marginal farmers.

ISSN: 3049-2289

Nutritional Importance, Future Prospects and Limitations of Quinoa (*Chenopodium Quinoa)*

N SABITHA, D JYOSHNA and C ANJANA
S V Agricultural College,Tirupati.

Introduction

Quinoa is a dicot annual plant belonging to Amaranthaceae. It is considered as pseudo cereal crop because the plant belongs to the family of spinach and sugar beets with woody stem, small leaves and panicle. Quinoa is native to South America. Quinoa (*Chenopodium quinoa* Willd.)is a climate rese has gained global attention owing to its remarkable tolerance to drought, salinity, frost, chilling, and low soil fertility, making it highly suitable for cultivation in arid, semi-arid, saline, and high-altitude regions (Mousa *et al*.,2025; Akram *et al*., 2024). Due to its rich potential contribution to food and nutritional security, the Food and Agriculture Organization (FAO) highlighted quinoa as a strategic crop for future agriculture (Sun *et al*., 2025). Domesticated more than 7,000 years ago in the Andean region of South America, quinoa has traditionally been cultivated in Peru and Bolivia (Fagandini *et al*., 2024; Delgado *et al*., 2024). Its recent global expansion is attributed to its broad ecological adaptability and ability to perform across diverse agro-climatic conditions (Cui *et al*., 2024).

Quinoa is an allotetraploid (2n = 4x = 36) and predominantly self-pollinated species, although limited natural outcrossing has been reported (Stephensen *et al.,*2025; Bazile, 2021; Del Pozo *et al*., 2023 It is mainly grown in chile, peru, Bolivia, Equador, Argentina and and recently introduced to Europe, Asia and Africa .Quinoa is a peudo cereal crop with gluten free making it as substitute for people with celiac disease or gluten intolerance (Cui et al., 2023). It is also called as functional food or golden grain (Younis et al., 2023).

Quinoa is a nutritional powerhouse, containing functional components which are quite essential for basic nutritional need. Also consists of good amount of phyto chemicals *viz.*, carbohydrates, saponins, phytosterols, phenolic compounds, bioactive peptides, polysaccharides and cellulose.(Zeyneb et al., 2021) . In addition to dietary fibre, essential minerals, vitamins and antioxidants (Hussain et al., 2021) quinoa has a high protein content and a balanced amino acid spectrum, with high levels of lysine and methionine (Nowak et al., 2016). These nutrient levels in quinoa are higher than those found in traditional grains, and quinoa possesses superior antibacterial (Pereira et al., 2019), antioxidant (Yu et al., 2024), hypocholesterolaemic, hypouricaemic (Zhong et al., 2023), and antihypertensive properties.(Table1) (Gonzalez et al., 2022c). Quinoa provides benefits for metabolism, diabetes, and cardiovascular diseases. It has been widely used in the food processing industry for its increasing recognition of the physiological activities and nutritional value. However, the quality of quinoa products varies substantially. The bioactive components of quinoa have received extensive attention from researchers both domestically and internationally, indicating its broad application prospects (Xi et al., 2024). However, in-depth research on the development and application of functional components, such as saponins, flavonoids, polyphenols, and pigments, remains limited. Additionally, consumers have a limited awareness of quinoa's nutritional value, resulting in restricted development of quinoa products and a relatively vacant niche in the consumer market.(Table 2)

Quinoa, an important food energy source, has been cultivated and consumed for over 6000 years. It comprises protein (13.8–16.5 % dry matter, DM), starch (32–69.7 % DM), and small amounts of minerals (Foste et al., 2015), such as calcium (87 mg/100 g) and iron (9.47 mg/100 g) (Ando et al., 2002), on a dry matter basis (Fig. 1). The fat content (2–9.5 %) is predominantly composed of unsaturated fatty acids, reaching as high as 71.1 % on a dry weight basis. Quinoa is a low-fructose, low-glucose food that exerts beneficial effects on glucose and lipid metabolism. Quinoa seeds have a high protein content of 12–18 %, which is higher than that of traditional crops such as barley (10.8 %), corn (10.2 %), and rice (7.6 %), and is comparable to wheat (14.3 %) (Wright et al., 2002). Additionally, its structure is related to edible quality and functional properties, such as its solubility, gel network formation, and emulsifying and foaming properties. Protein is one of the primary nutritional components in quinoa, mainly composed of 11S-type globulin (37 %) and 2S albumin (35 %), whereas the contents of prolamins (0.5–7 %) and 7S globulins (Wang et al., 2017) are relatively low. A large number of disulfide bonds in the spatial structure of quinoa proteins contribute to their stability.(Table 3)

Quinoa protein is not easily affected by the processing conditions and can maintain its original nutritional and functional characteristics. In addition to its nutritional value, quinoa protein hydrolysates exhibit higher solubility and higher anti-inflammatory activity than natural protein (Mahdavi-Yekta et al., 2019). Quinoa peptides are also resistant to digestion under gastric conditions but are further digested under small intestinal conditions. They maintain high antioxidant activity after gastrointestinal digestion, indicating future application of quinoa-derived active peptides in functional foods (Gu et al., 2024). Antioxidant peptides may prevent and treat cancers associated with reactive oxygen species (Sheih et al., 2010). Quinoa is rich in 17 amino acids, including eight essential amino acids for the human body and nine non-essential amino acids, with desirable bioavailability.(Table 2)

Starch is one of the primary components of quinoa and is one of the most abundant carbohydrates in its seeds, accounting for 32–69.7 % (Vega-Galvez et al., 2019) .Quinoa seed fibres are composed of pectins (4.7%), hemicellulose (41%), lignins (1.7%), and cellulose (52 %) and are classified as soluble dietary fibres. Fibre polysaccharides have various bioactive functions, such as anticancer, antioxidation, gastroprotective, bile acid-binding, cholesterol-lowering, food digestion inhibition, and immunomodulation (Sun et al., 2021; Wang et al., 2021). The fat content in quinoa is approximately 5.5–7.4 g/100 g, which is higher than that in wheat (1.7 %) and rice (0.7 %) (Repo et al.,2003). The fat content varies substantially among varieties, likely due to environmental factors affecting plant growth and fat accumulation, and exogenous conditions, such as soil conditions, precipitation, light, storage conditions. Quinoa contains up to 30 types of fatty acids, with polyunsaturated fatty acids accounting for approximately 82.7 %, mainly linoleic and linolenic acid. Quinoa is a good source of polyphenolic compounds and is closely related to antioxidant activity. Therefore, quinoa has great potential as a novel food antioxidant (Li et al., 2021). The antioxidant properties of quinoa render it suitable for a wide range of applications. In the food industry, it serves as an excellent raw material for functional foods and baked goods intended to have extended shelf lives. When used as a health supplement, it can prevent chronic diseases. In the recent past years, microbial resistance has become a global concern owing to the abuse of antibiotics. Identifying functional components from natural plants with good antibacterial activity is crucial for the prevention and treatment of foodborne diseases. Quinoa is rich in polyphenols and saponins, which exhibit antibacterial activity against foodborne pathogenic microorganisms.(Table 2 & 3)

ISSN: 3049-2289

Table 1: Relevant bioactive effects of quinoa extracts.

Property	Part	Components	Subject	Effects
Hypoglycaemic Activities	Seeds	All components	Type 2 diabetes mellitus (T2DM) mice model	Fasting blood glucose, glucose, high-density lipoprotein cholesterol, total cholesterol, triglyceride, and low-density lipoprotein cholesterol, the continuity and integrity of intestinal epithelial cells, the intestinal microflora richness
Anti-Hypercholesterolemic	Seeds	Novel Plant-Protein Derived Bioactive Peptides	Pancreatic lipase and cholesterol esterase	The potential CEase inhibitors: Peptide QHPHGLGALCAAPPST, HVQGHALPGVPAHW, and ASLNDPSPGTVM. The potential PL inhibitors: FSAGGLP, QHPHGLGALCAAPPST, KIVLDSDDPIFCGF, MVPVPH, and HVQGHALPGVPAHW.
Anti-inflammatory	Bran	Soluble dietary fiber	Dextran sodium sulphate induced ulcerative colitis in BALB/c mice	Weight, DAI scores and colonic shortening, the colonic cell apoptosis, tumour necrosis factor (TNF)-α, interleukin (IL)-1β, interleukin-10, mucin-2, zonula occludens-1, claudin-1, claudin-3, occludin, acetic acid and butyric acid
Anticancer activities	Seeds	Oil	HCT116 cell	Cell proliferation, floating dead cells, apoptosis of HCT116 cells
Immunity-enhancing activity	Seeds	Polysaccharides	Anti-cyclophosphamide (CTX)-induced immunosuppression in ICR mice	The recovery of thymus shrinking, spleen index, interferon-γ, interleukin-6, tumour necrosis factor,

ISSN: 3049-2289

				Immunoglobulin, lysozyme, the phagocytic index
Anti-aging	Seeds	Polysaccharides	D-galactose-induced mice	Swimming distance, escape latency, malondialdehyde, superoxide dismutase, glutathione peroxidase, and catalase

Table 2: Nutrient composition of Quinoa

Nutritional Components	Content	Unit	Origin
Protein	11.3–14.7	g/100 g	Peru
	11.6–13.7	g/100 g	Europe
	14.7–18.9	g/100 g	China
Starch	55.6–63.0	g/100 g	China
	53.2–61.3	g/100 g	Peru
	53.2–73.4	g/100 g	U.S.A
Dietary fiber	13.66–16.0	g/100 g	Peru
	7.7–15.9	g/100 g	Spain and the Andean
	12.71–18.59	g/100 g	Europe
Lipids	4.0–6.9	g/100 g	Peru
	4.9–6.5	g/100 g	Europe
	4.11–7.09	g/100 g	China
Phenolic compounds	30.3–59.7	mg/100 g	Peru
	46.7–68.2	mg/100 g	Canada
Flavanoids	75.3–87.58	mg/100 g	Europe
	51.5–141.95	mg/100 g	China
	66–202	mg/100 g	Africa, Egypt

ISSN: 3049-2289

Table 3:Nutrient composition of Quinoa in comparision with other cereal crops.

Composition	Quinoa	Wheat	Maize	Oats	Rye	Barley	Buckwheat	Rice
Protein (g/100 g)	11.3–18.9	10–18	7.8–11.2	12.1–14.1	10.8–12.7	10.8–13.6	11–17	7–8
Starch (g/100 g)	53.2–73.4	60–75	66–78	41–53	63–66	56.7–64.3	60–70	70–80
Dietary fiber (g/100 g)	7.7–18.59	1.14	1.4–2.2	8.8–13.4	1.5–2.0	3.5–5.4	3.4–6.5	0.2–0.9
Lipids (g/100 g)	4.0–7.09	2–2.5	4.1–12.3	4.4–7.2	1.7–2.1	2.4–3.4	2–3	1.3–1.8
Phenolics (mg/100 g)	30.3–202	46–134	60–460	320	136	45–135	70.4–124	48–467
Flavonoids (mg/100 g)	36.2–288	102	260	380	116.7	62–300.8	387	13.49–169.22
Tocopherol (μg/100 g)	0.4–1700	0–340	669–1300	721	68.4–290	747	0.1–8.51	70–190
Phytosterols (mg/100 g)	0.3–180	70–92	43.6	35–49	95.5	50.4	60	13.62–52.71
Saponins (mg/100 g)	2–244	–	–	0.02–0.05	–	–	–	–

Future prospects:

Quinoa possess ecological, biological, nutritional, and medicinal value. The grains contain higher protein, amino acid, and mineral contents than other ordinary grains, while its secondary metabolites exhibit various functional activities of medical, veterinary, and agronomic importance. Thus, to enhance the comprehensive utilization of this miracle crop lies with more in-depth research on the application mechanisms of the biological characteristics of quinoa in the fields of food, healthcare, and industry. Furthermore, a research gap remains regarding its specific targets in human clinical trials, especially in areas of cancer prevention and gut regulation. Overall, the interactions between quinoa and the body's naturally active substances should be fully considered to maximise the efficacy of its functionally active substances.

Limitations in popularising quinoa :

Genetic improvement of quinoa is limited and stands still especially in newly introduced regions. Consumer awareness should be increased on this emerging super food. There is every need to develop effective extraction technologies and consider their applications in other industries to maximise quinoa's functional characteristics. It is essential to strengthen the development and functional evaluation of quinoa-based foods and explore advanced processing and extraction technologies. Its consumption in large pockets of area is restricted due to higher price.

Conclusion:

The comprehensive utilisation of quinoa by-products and the production of high value-added products should be increased. Quinoa seed proteins and polysaccharides are regarded as having potential for designing delivery systems. It is promising material contributing to environmental protection and sustainability. It is evident that with the advancement of technology in cultivation and processing, this novel grain source will be more available and more information can be unravelled for future use.

References :

Akram, M. Z., Libutti, A., & Rivelli, A. R. (2024). Drought stress in quinoa: Effects, responsive mechanisms, and management through biochar amended soil: A review. Agriculture, 14(8), 1418. https://doi.org/10.3390/agriculture1408141 8

Bazile, D. (2021). Perspectives for sustainable agriculture under global changes: quinoa supporting food and nutrition security.

Cui, H., Li, S., Roy, D., Guo, Q., & Ye, A. (2023). Modifying quinoa protein for enhanced functional properties and digestibility: A review. Curr ent Research in Food Science, 7, 1006 04. https://doi.org/10.1016/j.crfs.2023.100604

Cui, H., Yao, Q., Xing, B., Zhou, B., Shah, S. S., & Qin, P. (2024). The performance of agronomic and quality traits of quinoa under different altitudes in northwest of China. Agronomy, 14(6), 1194. https://doi.org/10.3390/agronomy14061194

Del Pozo, A., Ruf, K., Alfaro, C., Zurita, A., Guerra, F., & Sagredo, B. (2023). Traits associated with higher productivity and resilience to drought-prone Mediterranean environments of coastal-lowland quinoa (Chenopodium quinoa Willd.). Field Crops Research, 299, 108985.

Delgado, H., Tapia, C., Manjarres-Hernández, E. H., Borja, E., Naranjo, E., & Martín, J. P. (2024). Phenotypic diversity of quinoa landraces cultivated in the Ecuadorian Andean region: In situ conservation and detection of promising accessions for breeding programs. Agriculture, 14(3), 336. https://doi.org/10.3390/agriculture14030336

Fagandini Ruiz, F., Villanueva, A., & Bazile, D. (2024). Chorematic modeling to represent dynamics in the quinoa agroecosystems in Peru. PLOS ONE, 19(4), e0300464. https://doi.org/10.1371/journal.pone.03004 64

Hussain, M. I., Farooq, M., Syed, Q. A., Ishaq, A., Al-Ghamdi, A. A., & Hatamleh, A. A. (2021). Botany, nutritional value, phytochemical composition and biological activities of quinoa. Plants, 10(11), 2258. https://doi.org/10.3390/plants10112258

Mousa, M. A., Asiry, K. A., Al-Qurashi, A. D., Almasoudi, N. M., & Elsayed, M. I. (2025). Genotypic variation in yield, physiological traits, and drought tolerance of quinoa (Chenopodium quinoa Willd.) under arid conditions. Frontiers in Plant Science, 16, 1679444. https://doi.org/10.3389/fpls.2025.1679444

Pereira, E.; Encina-Zelada, C.; Barros, L.; Gonzales-Barron, U.; Cadavez, V.; Ferreira, I.C.F.R. Chemical and nutritional characterization of Chenopodium quinoa Willd (quinoa) grains: A good alternative to nutritious food. Food Chem. 2019, 280, 110–114.

Stephensen, K. B., Costa-Tártara, S. M., Roser, R. L., Jarvis, D. E., Maughan, P. J., & Jellen, E. N. (2025). Germplasm pools for quinoa improvement. Crops, 6(1), 4. https://doi.org/10.3390/crops6010004

Sun, H., Khan, W. ud D., Tanveer, M., Ijaz, U., Lu, Z., & Shabala, S. (2025). Can quinoa (Chenopodium quinoa) replace traditional cereals under current climate scenarios? Frontiers in Plant Science, 16. https://doi.org/10.3389/fpls.2025.1636565

Younis, M., Sattar, D.-S., & Suleman, R. (2023). Quinoa (Chenopodium quinoa): Potential of the “golden grain” for food and nutritional security in South Asia. In Neglected plant foods of South Asia:

Exploring and valorizing nature to feed. https://doi.org/10.1007/978-3-031-37077- 9_14

Zeyneb, H., Pei, H., Cao, X., Wang, Y., Win, Y., & Gong, L. (2021). In vitro study of the effect of quinoa and quinoa polysaccharides on human gut microbiota. *Food science & nutrition*, *9*(10), 5735-5745.

Nowak, V., Du, J., & Charrondière, U. R. (2016). Assessment of the nutritional composition of quinoa (Chenopodium quinoa Willd.). *Food chemistry*, *193*, 47-54.

Zhong, L., Lyu, W., Lin, Z., Lu, J., Geng, Y., Song, L., & Zhang, H. (2023). Quinoa ameliorates hepatic steatosis, oxidative stress, inflammation and regulates the gut microbiota in nonalcoholic fatty liver disease rats. *Foods*, *12*(9), 1780.

González-Muñoz, A., Valle, M., Aluko, R. E., Bazinet, L., & Enrione, J. (2022). Production of antihypertensive and antidiabetic peptide fractions from quinoa (Chenopodium quinoa Willd.) by electrodialysis with ultrafiltration membranes. *Food Science and Human Wellness*, *11*(6), 1650-1659.

Xi, X., Fan, G., Xue, H., Peng, S., Huang, W., & Zhan, J. (2024). Harnessing the potential of quinoa: Nutritional profiling, bioactive components, and implications for health promotion. *Antioxidants*, *13*(7), 829.

Föste, M., Elgeti, D., Brunner, A. K., Jekle, M., & Becker, T. (2015). Isolation of quinoa protein by milling fractionation and solvent extraction. *Food and Bioproducts Processing*, *96*, 20-26.

Ando, H., Chen, Y. C., Tang, H., Shimizu, M., Watanabe, K., & Mitsunaga, T. (2002). Food components in fractions of quinoa seed. *Food Science and Technology Research*, *8*(1), 80-84.

Yuyuan, Y., Qingqing, Z., Liusha, Z., Xianglian, H., & Yongqing, S. (2024). Preparation, Characterization and Functional Study of Quinoa Polypeptide Complex with Food Polyphenols. *Journal of Chinese Institute of Food Science & Technology/Zhongguo Shipin Xuebao*, *24*(6).

ISSN: 3049-2289

Quantification of the Relationship Between Climate Variables And Net Primary Productivity of Forest Areas

Victor Thingujam[1], Umalaxmi Thingujam[2], Ongmu Lachungpa[3],
[1]ICAR–Research Complex for Eastern Region-Farming System Research Centre for Hill and Plateau Region, Plandu, Ranchi, Jharkhand – 834010, India
[2]Department of Soil Science and Agricultural Chemistry, Palli Siksha Bhavana (Institute of Agriculture), Visva-Bharati (Central University), Sriniketan, West Bengal, 731236 – India
[3]Forest and Environment Department, Govt. of Sikkim, Forest Secretariat Deorali, Gangtok, East Sikkim-737102

Climate strongly influences terrestrial ecosystem processes, particularly carbon sequestration and vegetation productivity. With the progression of global warming, climate is increasingly shifting from a regulating factor to a major ecological stressor, thereby threatening the resilience of forest ecosystems. Forests serve as one of the largest terrestrial carbon reservoirs and play a crucial role in the global carbon cycle through Net Primary Productivity (NPP). NPP is widely used to evaluate how forest productivity responds to climatic variability. Forest productivity is assessed using the MODIS MOD17A3HGF (Version 6.1) NPP dataset with a spatial resolution of 500 m, processed through the Google Earth Engine (GEE) platform. Climatic factors influencing forest productivity are obtained from the TerraClimate dataset, incorporating key climatic variables. The processed datasets are subsequently exported to the R statistical environment for spatial analysis. To investigate the complex causal relationships between climatic variables and forest productivity, a spatially explicit Piecewise Structural Equation Modelling (SEM) framework is applied. This approach enables the quantification of both direct and indirect climatic influences on NPP while accounting for spatial dependencies within the dataset. Overall, the integration of remote sensing data with eco-hydrological modelling provides a robust analytical framework for understanding climate–productivity relationships and offers important insights for climate adaptation strategies and sustainable forest management.

Introduction

Climate is widely recognized as one of the primary drivers impacting terrestrial ecosystem dynamics, affecting carbon sequestration, nutrient cycling and overall functioning of the ecosystem. But due to the continuing trajectory of global warming, climate is expected to shift from being a regulatory driver to becoming an increasingly significant stressor, thereby fundamentally challenging the resilience limits of ecosystems. (Bellard et al., 2012; Moritz & Agudo, 2013; Urban, 2015). According to the IPCC Sixth Assessment Report (2023), global surface temperature has already increased by approximately 1.1°C during 2011–2020 relative to 1850–1900.

Forests represent the largest biological reservoir of terrestrial carbon, accounting for approximately 80% of the planet's above-ground biomass (Pan et al., 2011). For quantification of this sequestration capacity, researchers rely on Net Primary Productivity (NPP). NPP denotes the quantity of atmospheric carbon fixed by plants after accounting for autotrophic respiration. As a sensitive indicator of plant physiological health, NPP provides a crucial proxy for evaluating shifts in ecosystem carbon balance under intensifying climatic variability. (Running et al., 2004; Zhao & Running, 2010).

Remote sensing offers an effective means of assessing NPP over complex and difficult terrain. Satellite-derived datasets, such as the MODIS NPP (MOD17) enables continuous monitoring of vegetation productivity and its relationship with climate at regional and multi-year scales (Zhao & Running, 2010).

ISSN: 3049-2289

Climate influences ecosystem productivity not solely through direct effects but also through complex interacting pathways. Traditional regression approaches often fail to disentangle these interconnected pathways. In such cases, Structural Equation Modelling (SEM) provides a framework to quantify both direct and indirect climatic effects on NPP.

Net Primary Productivity (NPP)Data

Forest productivity is quantified using the MODIS MOD17A3HGF (Version 6.1) NPP product at 500 m spatial resolution, processed within the Google Earth Engine (GEE) cloud-computing platform (Amani et al., 2020). To isolate forest carbon dynamics and remove noise from non-forest land covers, a spatial mask is created using the MODIS MCD12Q1 (Version 6.1) land-cover dataset. Annual NPP values is normalized using a 0.0001 scale factor to obtain standard productivity units of kg C m^{-2} $year^{-1}$. Temporal sequence for desired number of years is extracted, with annual mean forest NPP calculated for each year. Dataset is clipped to the study area boundary and filtered using the MCD12Q1 forest-only layer. The annual layers are reprojected to the WGS 84 / UTM zone 44N (EPSG:32644) coordinate system and concatenated into a single multi-band image stack to facilitate longitudinal trend analysis.


A


B

Fig. 1: A. Downloading of Raster layers of different variables from Google Earth Engine. **B.** Raster layers visualisation in Arc GIS Pro

Climatic Variables

Climatic drivers of forest productivity are derived from the TerraClimate dataset, which offers high-resolution (approx. 4 km) monthly climate and water balance variables generated through the integration of ground-based station observations and reanalysis data (Tanuja & Kumar, 2025). To ensure focussing the analysis exclusively on forested ecosystems, a spatial forest mask is created using the MODIS Land Cover (MCD12Q1) dataset. Desired variables are chosen to capture the multidimensional controls of the energy-water balance on vegetation productivity.

Data Processing And Statistical Analysis

The processed datasets are exported from Google Earth Engine (GEE) and imported into R for detailed spatial analysis using the raster, corrplot, pheatmap, virtualspecies, and sf packages. The analytical framework integrated the key variables: Actual Evapotranspiration (AET), Maximum Temperature (Tmax), Minimum Temperature (Tmin), Net Primary Production (NPP), Precipitation (PPT), Soil Moisture (SM), Vapor Pressure Deficit (VPD), and Wind Speed (WS).

Raster Alignment And Pre-Processing

To maintain spatial consistency, variables are aligned to a common grid system. Bilinear interpolation is applied to resolve differences in extent, resolution, and spatial projection, following established protocols for multi-source remote sensing integration (Li et al., 2026). The consistency of the alignment was verified using the compareRaster function. Temporal means for the study period are calculated for each variable to represent average conditions.

Multicollinearity And Correlation

Pearson correlation analysis examines the preliminary bi-variate relationships. A correlation matrix computes coefficients for the entire raster stack, with visualizations produced via corrplot and pheatmap (Hui et al., 2022). To ensure statistical robustness and avoid model over-fitting, the dataset is screened for multicollinearity using the remove Collinearity function from the virtualspecies package. (Leroy et al., 2016).

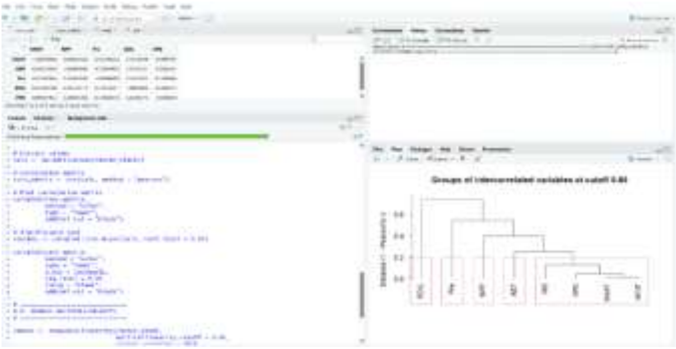


Fig. 4: Data processing, statistical analysis and statistical modelling in RStudio (R version 4.5.2)

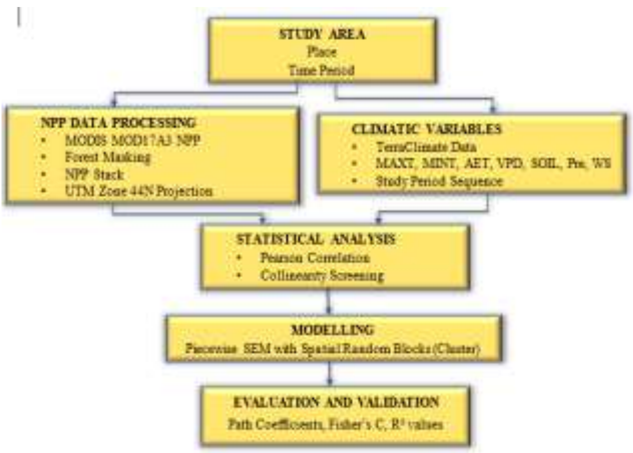
Structural Equation Modelling (SEM)

SEM quantifies the direct and indirect pathways through which climatic variables regulate forest NPP. SEM is well suited for ecological research as it evaluates complex multivariate relationships among i interdependent variables within a single causal network (Lefcheck, 2016)

SPATIAL PIECEWISE SEM FRAMEWORK

Unlike traditional variance–covariance-based SEM, Piecewise SEM utilizes local estimation, allowing the incorporation of hierarchical or nested random structures that conventional SEM cannot easily accommodate. To account for spatial dependency and autocorrelation inherent in the raster-derived dataset, study area is partitioned into spatial blocks based on geographic coordinates. These blocks are incorporated as random effects within Linear Mixed-Effects Models (LMMs) using the lme4 library (Lefcheck, 2016).

METHODOLOGY FLOWCHART



EVALUATION AND VALIDATION

All predictors are standardized to facilitate for the comparison of direct and indirect effect sizes (Li et al., 2026). Model performance is evaluated using Fisher's C statistic, where a $p > 0.001$ indicates that the model structure adequately represents the underlying data. Standardized path coefficients are extracted to distinguish the relative strength of climatic controls on forest productivity (Hu & Bentler, 1999).**CONCLUSION**

Climatic drivers governing forest NPP are assessed by employing a spatially explicit Piecewise Structural Equation Modelling (SEM) framework. The complex, interconnected pathways through which thermal regimes and moisture dynamics regulated carbon sequestration are successfully disentangled. The integration of SEM identifies the primary positive and negative driver of NPP showing which factors governs the forest productivity of the study area. Marginal and conditional variance indicates the model performance revealing the extent to which the selected climatic variables explain variations in NPP. Evaluating model accuracy helps to determine whether the climate variables included in the analysis adequately account for patterns of forest productivity, while also reflecting the potential influence of additional localized environmental factors. Combination of remote sensing with eco-hydrological SEM contributed a scalable analytical framework for assessing climate and forest productivity in complex mountainous terrains globally. This will provide a scientific foundation for informed climate adaptation and forest management.

REFERENCES

Amani, M., Ghorbanian, A., Ahmadi, S. A., Kakooei, M., Moghimi, A., Mirmazloumi, S. M., Moghaddam, S. H. A., Mahdavi, S., Ghahremanloo, M., Parsian, S., Wu, Q., & Brisco, B. (2020). Google Earth Engine Cloud Computing Platform for Remote Sensing Big Data Applications: A Comprehensive Review. *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing*, *13*, 5326–

5350. https://doi.org/10.1109/JSTARS.2020.3021052

Bellard, C., Bertelsmeier, C., Leadley, P., Thuiller, W., & Courchamp, F. (2012). Impacts of climate change on the future of biodiversity. *Ecology Letters*, *15*(4), 365–377. https://doi.org/10.1111/j.1461-0248.2011.01736.x

Calvin, K., Dasgupta, D., Krinner, G., Mukherji, A., Thorne, P. W., Trisos, C., Romero, J., Aldunce, P., Barrett, K., Blanco, G., Cheung, W. W. L., Connors, S., Denton, F., Diongue-Niang, A., Dodman, D., Garschagen, M., Geden, O., Hayward, B., Jones, C., … Ha, M. (2023). *IPCC, 2023: Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, H. Lee and J. Romero (eds.)]. IPCC, Geneva, Switzerland.* https://doi.org/10.59327/IPCC/AR6-9789291691647

Grace, J. B., Anderson, T. M., Olff, H., & Scheiner, S. M. (2010). CONCEPTS & SYNTHESIS EMPHASIZING NEW IDEAS TO STIMULATE RESEARCH IN ECOLOGY On the specification of structural equation models for ecological systems. In *Ecological Monographs* (Vol. 80, Number 1).

Hu, L. T., & Bentler, P. M. (1999). Cutoff criteria for fit indexes in covariance structure analysis: Conventional criteria versus new alternatives. *Structural Equation Modeling*, *6*(1), 1–55. https://doi.org/10.1080/10705519909540118

Hui, J., Chen, Z., Ye, B., Shi, C., & Bai, Z. (2022). Remote Sensing Monitoring of the Spatial Pattern of Greening and Browning in Xilin Gol Grassland and Its Response to Climate and Human Activities. *Remote Sensing*, *14*(7). https://doi.org/10.3390/rs14071765

Lefcheck, J. S. (2016). piecewiseSEM: Piecewise structural equation modelling in r for ecology, evolution, and systematics. *Methods in Ecology and Evolution*, *7*(5), 573–579. https://doi.org/10.1111/2041-210X.12512

Leroy, B., Meynard, C. N., Bellard, C., & Courchamp, F. (2016). virtualspecies, an R package to generate virtual species distributions. *Ecography*, *39*(6), 599–607. https://doi.org/10.1111/ecog.01388

Li, H., Xu, J., Ning, C., & Yu, X. (2026). Quantifying the spatiotemporal dynamics of net primary productivity under climate change using MOD17A3 NPP product and meteorological reanalysis datasets in the Yihe River Basin, East China (2001–2023). *Frontiers in Forests and Global Change*, *8*. https://doi.org/10.3389/ffgc.2025.1743125

Moritz, C., & Agudo, R. (2013). The Future of Species Under Climate Change: Resilience or Decline? *Science*, *341*(6145), 504–508. https://doi.org/10.1126/science.1237190

Running, S. W., Running, S. N. W., Nemani, R. R., Heinsch, F. A., Zhao, M., Reeves, M., & Hashimoto, H. (2004). A Continuous Satellite-Derived Measure of Global Terrestrial Primary Production. In *BioScience* (Vol. 54, Number 6).

Tanuja, & Kumar, R. (2025). Climatic shifts in the Beas Basin: A spatio-temporal analysis of time series of temperature and precipitation of TerraClimate dataset. *Science of the Total Environment*, *984*. https://doi.org/10.1016/j.scitotenv.2025.179712

Urban, M. C. (2015). Accelerating extinction risk from climate change. *Science*, *348*(6234), 571–573. https://doi.org/10.1126/science.aaa4984

Zhao, M., & Running, S. W. (2010). Drought-Induced Reduction in Global Terrestrial Net Primary Production from 2000 Through 2009. *Science*, *329*(5994), 940–943. https://doi.org/10.1126/science.1192666

ISSN: 3049-2289

Yellow Mealworm (*Tenebrio molitor* L.) as a Sustainable Aquafeed Ingredient: Nutritional Profile, Bioactive Compounds, and Role in Aquaculture

S. Suma Vishnu[1], Dr. P. Anand Prasad[2], P. Shanthanna[1]

[1]Ph.D. Scholars, Department of Aquaculture, College of Fishery Science, Muthukur, SPSR Nellore, Andhra Pradesh Fisheries University

[2]Assistant Professor & Head, Department of Aquaculture, College of Fishery Science, Muthukur, SPSR Nellore, Andhra Pradesh Fisheries University

Tenebrio molitor L. (Coleoptera: Tenebrionidae), commonly known as the yellow mealworm (YMW), has emerged as one of the most studied insect species for use in animal nutrition and aquaculture. Yellow mealworm larvae (YML) are considered a valuable insect species for animal feed due to their high nutritional values and ability to grow under different substrates and rearing conditions. This review consolidates current knowledge on the proximate composition, amino-acid and fatty acid profiles, mineral and vitamin content, bioactive compounds, and the role of YMW meal in aquaculture feed formulation across diverse species. Mealworms are well known for their high protein levels, well-balanced profile of amino acids, and good feed efficiency rate. Evidence increasingly supports their utility as a sustainable, functional replacement for conventional fish meal, with implications for growth performance, immune modulation, gut microbiome integrity, and product quality.

1.Introduction

Global aquaculture production is expanding quickly, increasing pressure on traditional protein sources such as fish meal (FM), which relies on wild fisheries that are already close to or exceeding sustainable limits. Consequently, research has focused on reducing FM levels in aquaculture feeds while maintaining fish health and product quality (Chemello et al., 2020). In this context, insects have emerged as promising sustainable feed ingredients within a circular economy framework. Among them, the yellow mealworm, *Tenebrio molitor* L., is considered one of the most suitable species for large-scale industrial production due to its adaptability and ability to thrive on grain-based substrates such as flour, bran, and other amylaceous commodities (Rumbos et al., 2020). Regulatory support has further encouraged its use; for instance, the European Union approved processed *T. molitor* proteins for aquaculture feed through Commission Regulation (EU) 2021/1372. Growing knowledge in entomophagy and animal nutrition has intensified research into the use of yellow mealworms as feed ingredients, supported by a rapidly expanding edible insect market projected to reach USD 16.39 billion by 2032 (Syahrulawal et al., 2023).

2. Biology and rearing of *Tenebrio molitor*

T. molitor is a holometabolous beetle with a complete life cycle comprising four stages: egg, larva, pupa, and adult (imago). The larval stage is the primary commercial product, as it concentrates the highest levels of protein and lipid. The nutrient composition of yellow mealworm (*T. molitor*) varies based on the stages of the life cycle, the rearing conditions, and the feeding substrate (Toviho et al., 2022).

The metamorphic stage of mealworms affects their chemical composition and nutritional values, with larvae and pupae generally sharing a common nutritional profile: lower contents of crude fibre, crude protein, and total amino acids, and higher crude fat, total fatty acids, and gross energy levels compared to adults (Toviho et al., 2022).

A critical advantage of YMW production is feedstock flexibility. Mealworms can potentially be grown under a variety of agricultural and other low-quality organic substrates, and can be utilized as alternative nutrient sources for livestock, mainly monogastric animals (Toviho et al., 2022). Rearing on locally available grain-based by-products such as wheat bran and oat by-products — can produce larvae with nutritional profiles comparable to commercial soybean meal (SBM), supporting regional feed sovereignty.

3. Nutritional Profile

3.1. Proximate Composition

The nutritional composition of *T. molitor* larvae varies depending on the rearing substrate but is generally characterized by high protein and lipid levels. On a dry matter basis, larvae contain approximately 48.21% protein, 34.21% lipids, 8.54% carbohydrates, 4.01% fibre, and 5.03% ash (De Matos et al., 2025). Diet significantly affects nutrient composition. Crude protein content ranges from **28–36%** when larvae are raised on different substrates, with the order lucerne > wheat bran > wheat flour > maize flour (López-Gámez et al., 2024). Similarly, larvae reared on fruit-waste-supplemented wheat bran showed protein values from 41.83% to 46.35%**,** along with variations in ash and fibre content. Larval age (8–12 weeks) has little effect on overall composition; however, larger larvae tend to have higher dry matter and fibre levels but lower chitin and nitrogen-free extract compared with smaller individuals (Toviho et al., 2022).

3.2. Amino Acid Profile

The protein in *T. molitor* larvae is considered nutritionally complete and meets the essential amino acid requirements recommended by FAO/WHO/UNU (Omar et al., 2026). Essential amino acids such as leucine and isoleucine are present in considerable amounts, contributing to a balanced protein profile. The total essential and non-essential amino acid composition of larvae and pupae is comparable to that of soybean meal (SBM)**,** suggesting that mealworms can serve as an effective alternative protein source in animal feeds (Toviho et al., 2022).

3.3. Lipid Profile and Fatty Acids

Mealworm larvae contain substantial lipid levels with a favourable fatty acid composition. The predominant fatty acids include oleic, linoleic, and palmitic acids, representing saturated, monounsaturated, and polyunsaturated fatty acid groups (López-Gámez et al., 2024). The high proportion of unsaturated fatty acids, particularly linoleic acid**,** enhances the nutritional quality of mealworm lipids (Gonzalez-de la Rosa et al., 2024). In aquaculture applications, mealworm oil has been evaluated as a replacement for fish oil. Studies with Pacific white shrimp (*Litopenaeus vannamei*) showed improved growth and feed utilization when diets included mealworm oil compared with fish-oil-based diets (Dalle & Palumbo et al., 2025).

3.4. Mineral Content

T. molitor larvae provide a wide range of essential minerals. High concentrations of potassium (16,710 mg/kg), phosphorus (10,339 mg/kg), and magnesium (3,041 mg/kg) have been reported, along with trace minerals such as zinc, iron, and selenium (Gonzalez-de la Rosa et al., 2024). Other important minerals include sodium, copper, and zinc, contributing to the larvae's overall nutritional value (López-Gámez et al., 2024).

3.5. Vitamins

Mealworm larvae also contain several vitamins, including vitamins A, B-complex, C, and E (tocopherol) (Gonzalez-de la Rosa et al., 2024). Vitamins C and E function as antioxidants, enhancing the nutritional quality of the larvae when used in food or feed applications.

3.6. Chitin

Chitin, a structural polysaccharide present in the insect exoskeleton, is an important nutritional consideration. Although chitin may have immunomodulatory effects, excessive levels can reduce protein and lipid digestibility in fish diets (El-Desouky et al., 2024). Therefore, mealworm inclusion levels should be optimized. Processing techniques such as defatting or enzymatic treatment (e.g., chitinase supplementation) can reduce chitin content and improve nutrient digestibility.

4. Bioactive Compounds

4.1. Antimicrobial Peptides (AMPs)

T. molitor is a potent source of endogenous antimicrobial peptides. Key AMPs characterized from this species include tenecin 1, tenecin 2 (active against Gram-positive bacteria), tenecin 3 (active against fungi), and tenecin 4 (targeting Gram-negative bacteria). These peptides are produced via the insect's innate immune system and represent a promising class of natural alternatives to antibiotics.

Yellow mealworm (*T. molitor*) larvae are increasingly recognized as a potential source of bioactive peptides due to their high protein content, with antimicrobial peptides from sustainable sources offering a spectrum of beneficial physiological effects (Omar et al., 2026). An Alcalase-based hydrolysis protocol produced peptide fractions with both antioxidant activity and antimicrobial action, effective against *Staphylococcus aureus* and *Escherichia coli*, with time-resolved hydrolysis experiments showing a progressive rise in free amino groups and a parallel increase in radical-scavenging capacity (Villanova et al., 2024).

Researchers have further explored the stimulation of AMP production by challenging larvae with bacteria. By injecting *T. molitor* larvae with *Lactiplantibacillus plantarum* to stimulate AMP production, and subsequently extracting the immunized *T. molitor* larval extract (iTME), the extract exhibited significant antimicrobial activity against Bacillus cereus, Staphylococcus aureus, Aspergillus flavus, and Aspergillus parasiticus, with a minimum inhibitory concentration (MIC) of 1 mg/mL (Gonzalez-de la Rosa et al., 2024).

4.2. Antioxidant Peptides

Enzymatic hydrolysis of YMW proteins using proteases such as Alcalase, Flavourzyme, and subtilisin releases bioactive peptides with measurable antioxidant capacity. The defatting process applied to mealworm flour was effective in reducing lipids by 82.5%, with a consequent increase of 38.4% in protein content, enabling enriched peptide fractions for bioactivity evaluation (Muñoz-Seijas et al., 2024).

Enzymatic hydrolysis in mealworm meal using commercial proteases yielded bioactive peptides with angiotensin-converting enzyme (ACE) inhibition capacity, antioxidant activity, and dipeptidyl peptidase IV (DPP-IV) activity (Muñoz-Seijas et al., 2024). Enzymatic hydrolysis using serine protease from Cucurbita ficifolia enhanced DPPH scavenging capacity from 3.15 to 8.17 µM Trolox/mL, demonstrating effective antioxidant bioactivation of *T. molitor* protein hydrolysates (Gonzalez-de la Rosa et al., 2024).

4.3. Anti-hypertensive and Metabolic Bioactive Peptides

YMW-derived peptides have demonstrated ACE-inhibitory and anti-diabetic (DPP-IV inhibitory) activities, making them candidates for functional food and nutraceutical applications. Studies have confirmed the potential for mealworm hydrolysates to produce bioactive peptides with antioxidant, antidiabetic, and antihypertensive properties, depending on the substrate composition and proteases employed (De Matos et al., 2025).

4.4. Chitin and Chitosan as Bioactive Agents

Beyond being an antinutritional factor at high concentrations, chitin and its derivative chitosan from *T. molitor* possess immunostimulatory, antimicrobial, and dye-adsorption properties. Chitin obtained from *T. molitor* larvae was highly effective in removing anionic and cationic dyes from aqueous solutions, being more efficient for anionic dyes at pH between 2 and 3 (Muñoz-Seijas et al., 2024). In aquaculture, low dietary chitin levels can stimulate the innate immune response in fish and crustaceans.

4.5. Phenolic Compounds and Vitamins as Antioxidants

Apart from protein, lipids, and chitin fractions, the presence of other compounds can be highlighted, such as minerals, phenolic compounds, and vitamins, all contributing to the overall bioactive and antioxidant value of *T. molitor* biomass (Muñoz-Seijas et al., 2024).

5. Role of *Tenebrio molitor* in Aquaculture

5.1. Regulatory Background

The inclusion of insect proteins in aquaculture diets was formally authorized in the European Union under Commission Regulation (EU) 2021/1372, permitting the use of processed animal proteins derived from seven insect species, including *T. molitor*, in feeds for non-ruminant farmed animals and aquaculture species. *Tenebrio molitor* (TM) is emerging as a sustainable alternative to fishmeal in aquaculture diets, gaining attention due to its balanced protein composition profile and low environmental footprint (Ihuț et al., 2025).

5.2. Finfish Species

5.2.1. Salmonids

In Atlantic salmon (Salmo salar), a 12-week growth trial assessed the effects of fishmeal substitution with defatted mealworm meal at 50% and 100% replacement levels in a recirculating aquaculture system, using a fishmeal-based control, and evaluated growth, physiobiochemical responses, digesta microbiome, and immune gene expression (Habte-Tsion et al., 2024).

Studies on rainbow trout (*Oncorhynchus mykiss*) have shown that the total substitution of fishmeal with insect meal is feasible with no negative effects on fish growth or on the digestibility of most nutrients, and hepatic enzymatic activities involved in amino acid metabolism and lipid synthesis were not negatively influenced by insect meal inclusion (Chemello et al., 2020).

5.2.2. Cichlids (Tilapia)

Fish fed with FM or *T. molitor* meal supplemented with sodium butyrate (1 g/kg) showed improved final body weight and weight gain over 60 days, demonstrating that co-supplementation strategies can enhance mealworm meal utilization in Nile tilapia (*Oreochromis niloticus*) (El-Desouky et al., 2024).

5.2.3. Marine and Other Freshwater Finfish

Numerous studies have revealed that *T. molitor* larvae meal can effectively replace a substantial proportion of fishmeal typically up to 60% in species such as rainbow trout (*Oncorhynchus mykiss*), European sea bass (*Dicentrarchus labrax*), sea bream (*Sparus aurata*), mandarin fish (*Siniperca scherzeri*), olive flounder (*Paralichthys olivaceus*), largemouth bass (*Micropterus salmoides*), and large yellow croaker (*Larimichthys crocea*) without compromising growth performance (Ihuț et al., 2025).

5.3. Crustaceans

5.3.1. Pacific White Shrimp (Litopenaeus vannamei)

L. vannamei has been among the most intensively studied crustacean species in relation to YMW meal supplementation. Feeding trials showed that it is possible to partially or completely replace fish meal with defatted yellow mealworm meal in isoproteic and isoenergetic diets, with optimal performances achieved at 50% fish meal replacement. Furthermore, shrimp fed the insect meal and then challenged with pathogenic bacteria causing early mortality syndrome (EMS) had significantly improved survival (Motte et al., 2019).

Replacing fishmeal with mealworm meal had a significant effect on the activities of superoxide dismutase (SOD), phenol oxidase (PO), lysozyme (LZM), acid phosphatase (ACP), alkaline phosphatase (ALP), and the total count of hemocytes (THC), suggesting that mealworm meal is a promising alternative protein source that enhances both growth performance and the immune system of *L. Vannamei*.

5.4. Immune Modulation and Disease Resistance

One of the most compelling attributes of YMW meal in aquaculture is its capacity for immunostimulation beyond mere protein replacement. YML has the potential to be used as an antimicrobial or bioactive agent to improve animal health and immune function in production animals (Khanal et al., 2023).

Bioactive compounds from insects are considered the future of the aquaculture industry, as ecologically sound alternatives to antibiotics are being sought to offer promising sustainability for disease prevention and/or control in aquaculture.

5.5. Gut Microbiome

Dietary substitution with mealworm meal alters the gut microbiome of fish, with conflicting reports across studies as to whether alpha diversity is statistically affected, which can be explained by differences in fish species, mealworm processing methods, and inclusion levels (Habte-Tsion et al., 2024).

5.6. Environmental and Sustainability Dimensions

Compared to conventional livestock farming, *T. molitor* rearing requires up to ten times less land, feed, and water, rendering it a more environmentally friendly alternative (Gonzalez-de la Rosa et al., 2024). The inclusion of yellow mealworms in the feed of rainbow trout lowered the utilization of net primary production and remaining water volume compared to a diet devoid of insect meal, though it had no impact on land use, acidification, eutrophication, global warming, or energy consumption.

6. Limitations

Despite substantial advances, several constraints persist:

Chitin and digestibility: High chitin content in full-fat or whole YMW meals remains a concern, as it impairs protein and lipid digestibility at inclusion levels above 40-50%. Defatting and enzymatic processing partially address this issue.

Bioavailability of bioactive peptides: Many of the reported bioactive effects remain confined to in vitro experiments or brief rodent trials. The inhibitory concentrations (IC50) reported for certain bioactive peptides, such as DPP-IV inhibitors, suggest that their potency may be too low to be physiologically relevant without further in vivo validation, and without pharmacokinetic and bioavailability data, translation into functional foods or nutraceuticals must be considered uncertain until clinical data are obtained (Muñoz-Seijas et al., 2024).

Substrate standardization: The substantial variability in nutritional composition driven by rearing substrate makes quality control and feed formulation challenging at commercial scale.

Cost competitiveness: Further efforts are needed to make *T. molitor* meal cost-competitive with conventional feed ingredients (Dalle & Palumbo et al., 2025).

7. Conclusions

Tenebrio molitor larvae present a compelling combination of high-quality protein, balanced amino acid profiles, favourable lipid composition, rich mineral and vitamin content, and a diverse repertoire of bioactive compounds including antimicrobial peptides, antioxidant hydrolysates, and chitin-derived immunostimulants. Their use as a fishmeal substitute in aquaculture is well-supported by feeding trials across a wide range of finfish and crustacean species, demonstrating benefits in growth performance, feed conversion, immune competence, and disease resistance. This systematic body of evidence highlights the nutritional richness of mealworm meal and its potential as a protein replacement for fishmeal used in the diets of various farmed fish and crustaceans. Future research should prioritize clinical validation of bioactive compounds, chitin management strategies, substrate optimization for consistent nutritional composition, and life-cycle economic modelling to support large-scale commercial adoption.

8. References

1. Chemello, G., Renna, M., Caimi, C., Guerreiro, I., Oliva-Teles, A., Enes, P., Biasato, I., Schiavone, A., Gai, F., & Gasco, L. (2020). Partially defatted Tenebrio molitor larva meal in diets for grow-out rainbow trout, Oncorhynchus mykiss (Walbaum): Effects on growth

performance, diet digestibility and metabolic responses. *Animals*, *10*(2), 229.

2. Dalle, Z. A., & Palumbo, B. (2025). The yellow mealworm (Tenebrio molitor L.) in animal nutrition: Advances and prospects for sustainable livestock production. *Biotechnology in Animal Husbandry*, *41*(2), 103-129.
3. de De Matos, F. M., & de Castro, R. J. S. (2025). Characterization and identification of potential antioxidant, antidiabetic, and antihypertensive peptides from hydrolysates of Tenebrio molitor flour and its protein concentrate. *Journal of Food Science*, *90*(10), e70595.
4. El-Desouky, F. F., Ibrahim, M. A., Abd El-Razek, I. M., El-Nabawy, E. S. M., Amer, A. A., Zaineldin, A. I., Gewaily, M. S., & Dawood, M. A. (2024). Improving yellow mealworm (Tenebrio molitor) utilization with sodium butyrate in Nile tilapia diets: effects on growth performance, intestinal histology, antioxidative response, and blood biomarkers. *Aquaculture Nutrition*, *2024*(1), 2442308.
5. Gonzalez-de la Rosa, T., Marquez-Paradas, E., Leon, M. J., Montserrat-de la Paz, S., & Rivero-Pino, F. (2025). Exploring Tenebrio molitor as a source of low-molecular-weight antimicrobial peptides using an in silico approach: correlation of molecular features and molecular docking. *Journal of the Science of Food and Agriculture*, *105*(3), 1711-1736.
6. Habte-Tsion, H. M., Hawkyard, M., Sealey, W. M., Bradshaw, D., Meesala, K. M., & Bouchard, D. A. (2024). Effects of fishmeal substitution with mealworm meals (Tenebrio molitor and Alphitobius diaperinus) on the growth, physiobiochemical response, digesta microbiome, and immune genes expression of Atlantic salmon (Salmo salar). *Aquaculture Nutrition*, *2024*(1), 6618117.
7. Ihuț, A., Răducu, C., Uiuiu, P., & Munteanu, C. (2025). From Gut to Fillet: Comprehensive Effects of Tenebrio molitor in Fish Nutrition. *Fishes*, *10*(9), 468.
8. Khanal, P., Pandey, D., Næss, G., Cabrita, A. R., Fonseca, A. J., Maia, M. R., Timilsina, B., Veldkamp, T., Sapkota, R., & Overrein, H. (2023). Yellow mealworms (Tenebrio molitor) as an alternative animal feed source: A comprehensive characterization of nutritional values and the larval gut microbiome. *Journal of Cleaner Production*, *389*, 136104.
9. López-Gámez, G., del Pino-García, R., López-Bascón, M. A., & Verardo, V. (2024). From feed to functionality: unravelling the nutritional composition and techno-functional properties of insect-based ingredients. *Food Research International*, *178*, 113985.
10. Motte, C., Rios, A., Lefebvre, T., Do, H., Henry, M., & Jintasataporn, O. (2019). Replacing fish meal with defatted insect meal (Yellow Mealworm Tenebrio molitor) improves the growth and immunity of pacific white shrimp (Litopenaeus vannamei). *Animals*, *9*(5), 258.
11. Muñoz-Seijas, N., Fernandes, H., Domínguez, J. M., & Salgado, J. M. (2025). Recent advances in biorefinery of Tenebrio molitor adopting green technologies. *Food and Bioprocess Technology*, *18*(2), 1061-1078.
12. Omar, M., Abdelhamid, A. M., Atea, M. A., Abdo, A. M., Fathy, M. M., & Maged, M. (2026). Tenebrio molitor as a sustainable source of proteins and bioactive peptides: extraction techniques, functional properties, and applications. *European Food Research and Technology*, *252*(3), 106.
13. Rumbos, C. I., Karapanagiotidis, I. T., Mente, E., Psofakis, P., & Rumbos, C. G. (2020). Evaluation of various commodities for the development of the yellow mealworm, Tenebrio molitor. *Scientific Reports*, *10*(1), 11224.
14. Sharifinia, M., Bahmanbeigloo, Z. A., Keshavarzifard, M., Khanjani, M. H., Daliri, M., Koochaknejad, E., & Jasour, M. S. (2023).

Fishmeal replacement by mealworm (Tenebrio molitor) in diet of farmed Pacific white shrimp (Litopenaeus vannamei): effects on growth performance, serum biochemistry, and immune response. *Aquatic Living Resources*, *36*, 19.

15. Syahrulawal, L., Torske, M. O., Sapkota, R., Næss, G., & Khanal, P. (2023). Improving the nutritional values of yellow mealworm Tenebrio molitor (Coleoptera: Tenebrionidae) larvae as an animal feed ingredient: a review. *Journal of Animal Science and Biotechnology*, *14*(1), 146.
16. Toviho, O. A., & Bársony, P. (2022). Nutrient composition and growth of yellow mealworm (Tenebrio molitor) at different ages and stages of the life cycle. *Agriculture*, *12*(11), 1924.
17. Villanova, J. C. V., Pretto, A., Penchel, E. M., Serra, S. D. S., Lanes, C. F. C., Ribeiro, V. B., Speroni, C. S., Bender, A. B. B., & Ferrigolo, F. R. (2024). Bioactive peptides from Tenebrio molitor: physicochemical and antioxidant properties and antimicrobial capacity. *Anais da Academia Brasileira de Ciências*, *96*, e20231375.

AGRICULTURE BULLETIN

ISSN: 3049-2289

Nutritional Interactions Between Natural Enemies and Target Pest Populations

Manihar Talukdar*, Mahesh Pathak and Pranab Dutta

School of Crop Protection, College of Post Graduate Studies in Agricultural Sciences, CAU(Imphal), Umiam, Meghalaya – 793103, India.

For an effective biological control, the nutritional interactions between the natural enemies and their target pest population in essential. The natural enemies like different predators (praying mantids, green lacewing, ladybird beetle etc.) and parasitoids (*Trichogramma spp., Bracon habitor, Gonoizas nephantidis,* etc.), though primarily rely on pests for their protein sources, supplemental sources like nectar, pollen and honeydew can influence the reproduction, foraging and persistence and these dynamics can enhance pest suppression through improved enemy fitness. However, the competition for prey may disrupt the balance and predator-prey dynamics in a nutrient-poor habitat. Strategies like conservation of landscape complexity may boost these dynamics by increasing non-host availability and promoting enemy complementarity for sustainable pest regulation.

Introduction

Nutrition refers to the process of converting food into bodily components and energy for daily activities. The genetic control of an organism's synthetic capacities determines its nutritional requirements. Entomophagous insects feed on fat and protein-rich insects to obtain energy. Natural enemies require a variety of resources, including food, water, nesting places, and protective habitats. Some adversaries may have sufficient resources within a specific crop, while others may demand more sophisticated resources. Finding a way to proliferate and generate these entomophages for release in biological control measures is the primary objective of research on the nutritional ecology of entomophagous insects, which is typically conducted to enhance synthetic rearing techniques. Larvae typically have larger nutritional needs than adults, except for reproduction, and these needs vary depending on the stage and physiological state. Natural enemies' nutrition is a complicated and tritrophic interplay of physiological, behavioural, and ecological elements involving the entomophage, its host, and the host's food source. Since most predators and parasitoids are omnivores, they must eat non-prey items like pollen and nectar. Access to blooming resources is necessary and/or advantageous for natural enemies belonging to a wide variety of orders, including Hymenoptera, Diptera, Coleoptera, Heteroptera, Neuroptera, Araneae, and Acarina. The activity, longevity, and fecundity of these predators and parasitoids can all be markedly increased by access to pollen and nectar (Hogg *et al*., 2011). Insects require protein, 10 essential amino acids (arginine, histidine, isoleucine, leucine, lysine, methionine, phenylalanine, threonine, tryptophan, and valine), the B-vitamin complex (biotin, folic acid, nicotinic acid, panthothenic acid, pyridoxine, riboflavin, and thiamin), water-soluble growth factors like choline and inositol, fat-soluble vitamins, and cholesterol. Entomophagous insects do not have specific nutritional requirements. However, Thompson (1981) found that *Exeristes roborator* larvae can develop on diets lacking critical amino acids and B-complex vitamins.

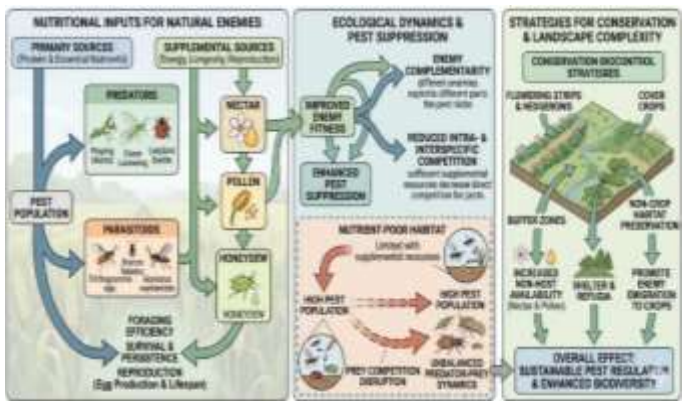


Figure 1: Nutritional Interactions in Biological Pest Control (Made with Google Gemini)

Nutrition and Foods of Parasitoids:

Nutrients, especially sugars and free amino acids, are abundant in pollen and nectar. They play a crucial role in parasitism and maximising life span (Heimpel *et al*., 2005). According to lab testing, parasitoids that are not fed sugar or honey solutions enhanced with other nutrients typically exhibit lower fecundity and longevity. Since parasites are carnivores at all developmental stages, they need meals that are higher in protein and lower in fat and carbohydrates. Adult hymenopterous and dipterous parasitoids also frequently consume honeydew, which is the excrement of homopterous insects. In general, honeydew has more proteinaceous material than nectar. The dietary needs for oogenesis and embryogenesis have an impact on how female parasitoids feed. Parasitoids are classified according to the development and maturation of their eggs as follows:

- **Proovigenic**: Proovigenic parasites are generally koinobiontic endoparasites, meaning the host continues to feed, grow, and survive even after the parasitism. They feed to be healthy and able to lay eggs. Females of proovigenic species complete oogenesis (differentiation of the ovum into a cell capable of continued development when fertilised) before eclosion and typically lay eggs shortly after emergence (Segoli *et al*., 2018).

- **Synovigenic:** Females of synovigenic species are idiobiontic ectoparasites, immobilising the host and preventing further development. Adults arise without a complete set of developed eggs. Adults typically live longer than proovigenic parasitoids. Synovigenic parasitoids lay big, yolk-rich eggs with enough reserves to complete development before oviposition. These parasitoids require nourishment to produce eggs. Synovigenic parasite larvae have limited dietary resources as host development stops after parasitism.

- **Idiobionts and Koinobionts:** Idiobionts are ectoparasites found in host eggs or pupae. Idiobionts quickly kill their hosts through venom or feeding. The nutritional resources of idiobionts are exclusively determined by host size. Idiobiontic species have a positive connection with host size, parasite size, overall biomass, and parasitoid population.

Koinobionts are typically endoparasites of numerous host stages or larval-pupal endoparasites. Koinobionts rely on the host's ongoing feeding, growth, and development for their nutritional needs. Oinobionts adapt their development rates to the host's available resources (Cuny and Poelman, 2022).

The host's nutrition affects parasitoid development and survival, as well as the sex ratio, fecundity, lifespan, and vigour of adult wasps. Solitary parasitoids grow in proportion to host biomass, with larger parasitoids emerging from larger hosts. This relationship applies to parasitoids that attack all stages of the host's development, but also to parasitoids that target host eggs and pupae with a set host size. Adult Trichogramma pretiosum reared on five host eggs exhibited a direct link between parasitoid size and host egg volume. The success of parasitoids in parasitisation activity is directly related to nutritional factors (Holmes *et al*., 2023). Parasitoid fecundity, reproductive size, sex ratio and longevity are correlated with host size and nutritional factors.

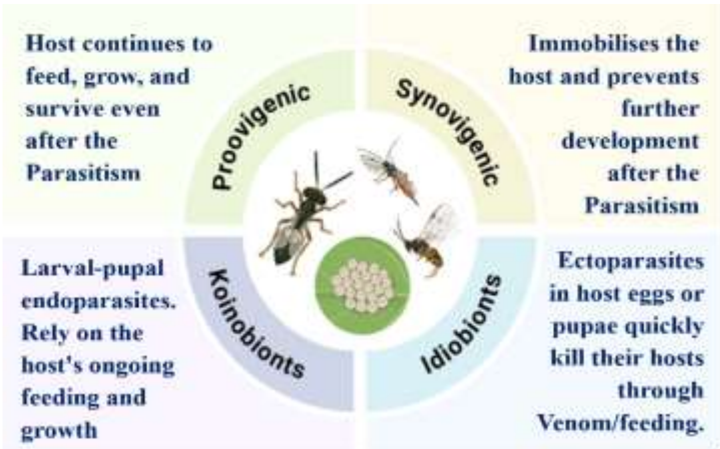


Figure 1: Types of Parasitoids based on the development and maturation of their eggs

Nutrition and Foods of Predators:

Entomophagous insects, which feed on other insects, require specialised nutrients for growth, development, and reproduction. Their nutritional requirements vary based on their life stage (larvae, pupae, or adults) and the prey they ingest. Nutritional requirements are determined by the organism's synthetic capacities, which are genetically controlled. Parasites and predators have similar nutritional requirements as free-living insects (Thompson, 1999). Identification of key nutritional elements for growth, development, and reproduction leads to successful feeding and raising of natural enemies in the absence of natural food sources. Natural enemy nutrition is a complex combination of physiological, behavioural, and ecological aspects between the entomophage, host, and food source. Insect hosts provide food and shelter for both larval and adult parasitoids. Insects use various "antiparasitoid" techniques to combat potentially harmful parasites that invade their bodies. After successfully invading, insects modify the host body to better suit their needs and living conditions. Maintaining nutritional intake is crucial for the parasite's proper functioning. Entomophagous insects need access to different hosts, overwintering habitats, a consistent food supply, and suitable microclimates to live. Most predators and parasitoids are omnivores that eat non-prey foods like pollen and nectar. Entomophagous insects from Hymenoptera, Diptera, Coleoptera, Heteroptera, Neuroptera, Araneae, and Acarina gain access to floral resources. Access to pollen and nectar sources boosts predator and parasite activity, longevity, and fertility. Flowering resources are crucial for natural enemies to effectively manage pest insects (Cloyd, 2020). Flowering plants serve non-prey requirements, providing resources for predator and parasite populations throughout the season. Predaceous insects rely on plants for nourishment, either as their primary source (for non-predaceous species) or as a supplement (for predatory species). Idiobiontic parasites require carbohydrate, amino acids, vitamins, and inorganic salts to produce eggs, but non-predaceous adults merely need sugar and water to survive and reproduce. Predaceous adults require prey to maintain oviposition (Cuny and Poelman, 2022).

Role of nutrients:

1. **Nitrogen:** Entomophagous insects demand heavily on nitrogen supplies due to their rapid growth (Grenier *et al*., 1974). Carnivorous parasitoids and predators require a protein-rich diet, including aromatic amino acids for cuticle tanning during larval development (Bonnot *et al*., 1976). Free amino acids, such as phenylalanine, can be poisonous at high concentrations or have little solubility, prompting the use of tyrosine-rich peptides or proteins to transport aromatic amino acids (AA). While the 10 "essential" AAs are necessary, other ones are also useful for normal growth. Some species require free AA to maintain appropriate osmotic pressure (OP), while others rely on proteins, hydrolysed proteins, or peptides. The most commonly utilised proteins include casein, lactalbumine, ovalbumine, serum albumine, soybean extract, and yeast.

2. **Lipids:** Many parasitoids have similar total fatty acid compositions to their hosts, indicating that they may mimic the host makeup (Delobel and Pageaux, 1981). It could be the same for predators (Sighinolfi, 2008). Eicosanoids, mostly generated from arachidonic fatty acids, have been linked to various insect functions, including reproduction and immunology. Polyunsaturated fatty acids may be necessary for appropriate growth in entomophagous insects. To achieve homogeneous dispersion in the aqueous phase, free fatty acids or triglycerides must be combined with emulsifying agents. Emulsifying agents include Tween 80, lecithin (phosphatidylcholine), and lauryl sulphate. Egg yolk, commonly used in artificial media for egg parasitoids, has large quantities of emulsified fatty acids, cholesterol, and lecithin.

3. **Carbohydrates:** Carbohydrates, like some lipids, are commonly used as energy sources. Although carbs are not necessary, glucose

AGRICULTURE BULLETIN ISSN: 3049-2289

promotes development and lipogenesis, leading to an increase in unsaturated fatty acids. Trehalose, a non-reducing disaccharide often found in insects, is crucial for metabolism and stress resistance (Qin *et al*., 2011). Insects rely heavily on trehalose, a non-reducing disaccharide, for metabolism and stress resistance (Qin *et al*. 2011). It can be utilised as a substitute for sucrose or glucose, as well as partially replacing haemolymph in Trichogramma medium. To lower OP in the medium/diet, it is recommended to replace oligosaccharides with polysaccharides, such as glycogen. However, because OP is not important for many predators, sucrose has been used instead of glycogen to reduce diet costs. Sucrose may stimulate both parasitic and predatory insects to feed.

4. **Inorganic salts:** Insects require inorganic salts for normal development. However, the balance of captions, particularly K+/Na+, differs depending on species. *G. punctipes*, a predator, prefers meals with a higher K/Na ratio compared to those with lower ratios.

5. **Vitamins:** Accurately determining vitamin requirements in delicate trials using vitamin-free ingredients and egg stocks. The requirements are identical as those of other insects. Typically, diets contain 12 vitamins, mostly hydro-soluble (vitamins B and C) and two liposoluble (retinol-A and tocopherol-E).

6. **Miscellaneous:** The incorporation of ribonucleic acids (RNA) in the medium/diet promotes survival and growth. Trichogramma females require mineral cations, and a balanced ratio of K+ to Mg++ has been shown to increase oviposition.

7. **Other physiological requirements:** Endo-parasitoids rely on their environment as well as their food source for survival during their larval stage. The medium must meet nutritional requirements, have appropriate physicochemical properties, and support critical physiological functions such as respiration, excretion, and protection.

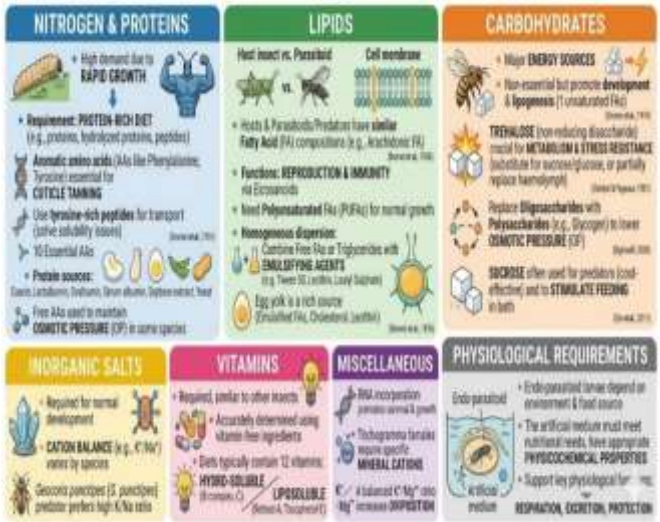


Figure 2: Role of Nutrients in Entomophagous Insect Nutrition (Made with Google Gemini)

Conclusion

Natural enemies' ability to survive, reproduce, and function as a whole is greatly impacted by their nutritional needs, which include access to pollen, nectar, and other sources of prey. Conservation biological control is essential for maximising the effects of natural enemies by supplying sufficient nutrients and modifying the environment to increase their numbers. Furthermore, anticipating and controlling pest outbreaks requires an understanding of the dynamics of predator-prey interactions, including functional and numerical responses. Although density-dependent mortality plays a significant role in population management, creating successful biological control measures requires an appreciation of the complexity of real-world systems and a more sophisticated knowledge of density-vague interactions. In conclusion, biological control is a sustainable pest management strategy that reduces environmental effects and promotes ecological equilibrium. Further research in areas including nutritional ecology, population dynamics, and habitat alteration can improve our understanding of natural enemy-pest interactions and improve biological control in agricultural and natural environments.

References:

Bonnot, G., Delobel, B. and Grenier, S. (1976). Composition corporelle en acides aminés du parasitoide Phryxe caudate Rond. (Diptera) au cours de sa croissance larvaire. *J Insect Physiol*, 22: 505-514.

Cloyd, R.A. (2020). How Effective Is Conservation Biological Control in Regulating Insect Pest Populations in Organic Crop Production Systems? *Insects*. 11(11):744. doi: 10.3390/insects11110744. PMID: 33138249; PMCID: PMC7692856.

Cuny, M.A.C., Poelman, E.H. (2022). Evolution of koinobiont parasitoid host regulation and consequences for indirect plant defence. *Evol Ecol*. 36(3):299-319. doi: 10.1007/s10682-022-10180-x. Epub 2022 May 9. PMID: 35663232; PMCID: PMC9156490.

Delobel, B. and Pageaux, J.F. (1981). Influence de l'alimentation sur la composition en acides gras totaux des Diptères Tachinaires. Entomol. *Exp. Appl*., 29: 281-288.

Grenier, S., Bonnot, G. and Delobel, B. (1974). Definition et mise au point de milieux artificiels pour lelevage in vitro de Phryxe caudata Rond. (Diptera, Tachinidae). I-Survie du parasitoide sur milieux dont la composition est basee sur celle de hemolymphe de hote. Ann. *Zool. Ecol. Anim*., 6: 511-520.

Heimpel, G.E. and Jervis, M.A. (2005). Does floral nectar improve biological control by parasitoids? In: Wäckers FL, van Rijn PCJ, Bruin J, eds. *Plant-Provided Food for Carnivorous Insects: A Protective Mutualism and Its Applications*. Cambridge University Press; 267-304.

Hogg, B.N., Bugg, R.L. and Daane, K.M. (2011). Attractiveness of common insectary and harvestable floral resources to beneficial insects. Biological Control, 56: 76-84.

Holmes, L.A., Nelson, W.A. and Lougheed, S.C. (2023). Strong effects of food quality on host life history do not scale to impact parasitoid efficacy or life history. *Sci Rep* 13: 3528. https://doi.org/10.1038/s41598-023-30441-1

Pelosse, P., Jervis, M. A., Bernstein, C. and Desouhant, E. (2011). Does synovigeny confer reproductive plasticity upon a parasitoid wasp that is faced with variability in habitat richness? *Biological Journal of the Linnean Society,* 104(3): 621–632. https://doi.org/10.1111/j.1095-8312.2011.01741.x

Qin, Z., Zhang, F., Wang, S., Zhang, Y., Tang, B., Xu, H. and Bao, Y. (2011). A trehalose 6- phosphate synthase gene of the ladybird Harmonia axyridis: cloning, the expression and its function under various stress conditions. In Proceedings of Inter. Sympo. Mass Production and Commercialization of Arthropod Biological Control Agents, Beijing, China, p. 36.

Segoli, M., Sun S., Nava, D.E., Rosenheim, J.A. (2018). Factors shaping life history traits of two proovigenic parasitoids. Integrative Zoology 13: 297–306.

Sighinolfi L., Febvay G., Dindo ML., Rey M., Pageaux JF., Baronio P. and Grenier S. (2008) Biological and biochemical characteristics for quality control of Harmonia axyridis (Pallas) (Coleoptera, Coccinellidae) reared on liver-based diet. Archiv. Insect Biochem. Physiol., 68: 26-39.

Thompson S.N. 1999. Nutrition and culture of entomophagous insects. *Annual Review Entomology*. 44:561-592. https://doi.org/10.1146/annurev.ento.44.1.561

AGRICULTURE BULLETIN
ISSN: 3049-2289

Digital Kiosks: Bridging the Information Gap in Rural Extension

Reihana Tampakmayum[1], Maitarambum Wartung Monsang[1*] and Sahid Ahmad Tampakmayum[1]
[1]Department of Fisheries Extension, Economics and Statistics, College of Fisheries, Lembucherra, Central Agricultural University, Imphal, India

Agricultural extension systems play a pivotal role in transferring scientific knowledge and technological innovations from research centres to farming communities, thereby supporting rural livelihoods and food security. Conventional delivery mechanisms, however, remain hampered by geographic limitations, staff shortfalls and delays in information provision — constraints especially acute in remote areas. The rapid growth of information and communication technologies (ICTs) has created new pathways for revamping rural advisory services. Among emerging interventions, digital kiosks have attracted attention as community-level interactive platforms capable of delivering agricultural guidance, welfare programme details and advisory services to village farmers. This article examines the conceptual basis of digital kiosks, their utility as extension teaching aids, the range of services they can provide, their benefits for extension systems and the operational barriers to large-scale deployment. It concludes that digital kiosks hold significant promise for strengthening extension outreach when supported by reliable infrastructure, vernacular interface design and sustained digital literacy programmes.

Introduction

Extension education serves as an indispensable conduit for transferring scientific knowledge and evidence-based farming practices from research institutions to rural communities (Michael and Ogunsola, 2021). By engaging farming households systematically, extension systems cultivate the competencies needed for improved resource management and technology adoption (Ongachi and Belinder, 2025), making substantive contributions to national agricultural development (Sameer, 2023). Historically, extension delivery has centred on interpersonal approaches — field demonstrations, group meetings and farm visits — which have proven effective in building farmer trust and accelerating grassroots technology uptake (Jeet and Kumar, 2024; Vikas *et al.,* 2020). Yet conventional systems remain constrained by personnel shortages, escalating costs and delays in communicating time-sensitive information (Chapman *et al.,* 2003). As agricultural systems grow more complex owing to climate variability and market volatility, the imperative for rapid, inclusive information dissemination has intensified (Zhang *et al.,* 2016). Failure to deliver critical information within decision windows exposes smallholders to avoidable yield losses (Ireri *et al.,* 2021).

Recent ICT advances have expanded available tools for strengthening extension (Mulungu *et al.,* 2025). Mobile applications, web-based platforms and multimedia tools are complementing conventional methods by enabling geographically wider knowledge sharing (Priya *et al.,* 2025). Among these innovations, digital kiosks are increasingly recognised as a viable modality for reaching rural communities where personal device ownership and internet access remain limited (Steinke *et al.,* 2021).

Understanding Digital Kiosks

Digital kiosks are standalone, self-service electronic terminals enabling users to access digital content through touchscreen interfaces, equipped with internet connectivity and purpose-built software that allow information retrieval without dependence on intermediaries (Aljohi *et al.,* 2023). A key advantage over mobile-based systems is their installation at fixed community locations, making them simultaneously accessible to multiple users regardless of individual device ownership (Martinez *et al.,* 2024). Although kiosks have served banking, transportation and civic administration for years, their potential for rural development is rapidly being recognised. In agricultural settings, they can be configured to deliver crop advisories, weather bulletins, real-time market prices and government scheme details (Sharma *et al.,* 2017). Strategic placement at high-footfall locations — panchayat offices, Krishi Vigyan Kendras (KVKs), cooperative societies, mandis and community centres — ensures farmers encounter these services during routine activities (Falahati *et al.,* 2025).

Fig. 1: Digital kiosk as a village-level information hub: range of agricultural and rural development services delivered through community-based interactive kiosk platforms

Digital Kiosks as Extension Teaching Aids

The intersecting pressures of climate change, volatile markets and rising input costs demand that farmers continuously update their knowledge in near real time (Lubell *et al.,* 2014). Digital kiosks support this by placing multimedia learning resources — text advisories, photographic guides, audio content and instructional videos — directly within farming communities (Sousa *et al.,* 2016). As a core component of e-Extension, these platforms render complex technical concepts accessible to farmers across educational levels (Singh, 2024). Beyond serving as information repositories, kiosks also function as interactive extension contact points, enabling real-time guidance on crop health, pest management and agrometeorological forecasts, thereby improving extension responsiveness (Sen *et al.,* 2025).

Types of Information Delivered Through Digital Kiosks

Deployed as village-level information hubs, digital kiosks can provide a broad suite of services. Real-time market intelligence allows farmers to monitor commodity prices across mandis, facilitating strategic decisions on produce sales (Qaisar *et al.,* 2011). Technical guidance on high-yielding varieties, fertiliser schedules, integrated pest management and seasonal cultivation practices directly supports productivity improvement (Sangbuapuan and Guha, 2016). Agrometeorological services — weather forecasts and rainfall advisories — address a critical information gap for smallholders, enabling better scheduling of sowing, irrigation and harvesting (Subrahmanyam *et al.,* 2012). Online consultation interfaces facilitate farmer-expert interaction, connecting communities with otherwise geographically inaccessible agricultural scientists (Antapurkar *et al.,* 2024). Kiosks can further disseminate details of subsidies, crop insurance and institutional finance options facilitated by NABARD and state departments (Rajagopal *et al.,* 2021), while also raising awareness of allied sectors — fisheries, aquaculture and animal husbandry — to encourage income diversification (Subrahmanyam *et al.,* 2012).

Benefits of Digital Kiosks in Rural Extension

The strategic integration of digital kiosks into rural extension frameworks yields several notable benefits. Most immediately, kiosks democratise information access at the village level, eliminating time-consuming journeys to distant extension offices (Subrahmanyam *et al.,* 2012; Martinez *et al.,* 2024) and reducing information asymmetry between research institutions and farming communities (Singh *et al.,* 2023). Their potential as community learning centres supports rural human capital development through on-demand access to instructional videos and structured digital training content (Singh *et al.,* 2024; Mulungu *et al.,* 2025).

ISSN: 3049-2289

From a development perspective, kiosks advance digital inclusion goals, encouraging adoption of broader e-governance services (Touri, 2021; Ireri *et al.,* 2021). They also facilitate more direct producer-market linkages, reducing dependence on intermediary chains and contributing to improved farmgate prices and household income (Subrahmanyam *et al.,* 2012; Ireri *et al.,* 2021).

Challenges and Limitations

Large-scale kiosk deployment faces several interrelated challenges. Low digital literacy among farming communities substantially limits utilisation rates, as many users struggle to navigate interfaces or interpret screen-based content (Coleman *et al.,* 2008). Infrastructural constraints — unreliable electricity and inadequate broadband connectivity — undermine operational reliability; without stable infrastructure, kiosk investments risk suboptimal returns (Mulungu *et al.,* 2025; Sen *et al.,* 2025). Content available exclusively in English or a national language may exclude farmers literate only in regional vernaculars, diminishing the equity dimensions of kiosk-based extension (Coleman *et al.,* 2008; Martinez *et al.,* 2024). Capital procurement costs combined with recurring maintenance expenses present financial sustainability concerns, while inadequate post-installation upkeep results in system downtime that erodes farmer confidence (Sen *et al.,* 2025; Subrahmanyam *et al.,* 2012). Ultimately, digital platforms cannot replace the relational dimensions of human-mediated extension, which remain irreplaceable in motivating behavioural change and contextualising recommendations to local realities (Cho and Fiorito, 2010).

Way Forward: Strengthening Rural Extension Through Digital Kiosks

Realising the full potential of digital kiosks requires deliberate enabling conditions. Interface design should prioritise simplicity and visual intuitiveness guided by universal design principles and content must be offered in regional languages, complemented by pictorial representations and audio-visual materials that transcend literacy barriers (Aljohi *et al.,* 2023; Coleman *et al.,* 2008; Martinez *et al.,* 2024; Sen *et al.,* 2025). Kiosk introduction must be paired with systematic capacity building — training programmes, community demonstration events and awareness campaigns for both farmers and extension workers, who are well-positioned to serve as community-level digital facilitators (Jeet and Kumar, 2024; Singh *et al.,* 2024). Sustained investment in last-mile broadband connectivity, reliable power supply and solar backup systems requires coordinated engagement among government agencies, agricultural universities and private technology partners (Mulungu *et al.,* 2025; Steinke *et al.,* 2021). Most productively, kiosks should complement rather than displace existing approaches; combining digital tools with farmer field schools, method demonstrations and group meetings creates hybrid advisory systems with coverage and effectiveness neither modality could achieve alone (Steinke *et al.,* 2021; Vikas *et al.,* 2020).

Fig. 2: A Hierarchical Strategic Framework for the Sustainable Integration of Digital Kiosks within Rural Agricultural Extension Systems

Conclusion

Digital kiosks represent a strategically significant instrument for modernising agricultural extension in rural India, offering farming communities a convenient, multimedia-rich gateway to the knowledge needed to navigate an increasingly complex agricultural environment. Their transformative potential can be fully realised only when deployment is accompanied by investment in rural digital infrastructure, institutionalised digital literacy programmes, meaningful involvement of extension professionals and a firm commitment to content localisation and inclusive design. Purposeful integration of digital kiosks into rural extension architecture can meaningfully contribute to both sustainable agricultural development and enhanced rural livelihoods.

References

Aljohi, A. S., Alzaabi, S. S., Almahri, R. S., Tsaramirsis, G., and Hamid, O. H. (2023). Navigating the Divide: Digital Kiosks and Mobile Apps as Complementary Human-Centered Self-Service Technologies. *Engineering Proceedings*, *59*(1), 162.

Antapurkar, S., Karadkhele, J., Kokane, S. R., and Kadam, A. (2024). Enhancing Agriculture: Implementing Web Application for Agriculture Solutions from Experts. In 2024 8th International Conference on Computing, Communication, Control and Automation (ICCUBEA) (pp. 1-5).

Chapman, R., Slaymaker, T., and Young, J. (2003). Livelihoods approaches to information and communication in support of rural poverty elimination and food security (pp. 53-68). London, UK: Overseas Development Institute.

Cho, H., and Fiorito, S. S. (2010). Self-service technology in retailing. The case of retail kiosks. Symphonya. Emerging Issues in Management, (1), 43-55.

Coleman, E., De Bruyn, J., and Dlamini, T. (2008). Factors influencing the utilization of the public Internet terminal system in two rural communities. *South African Journal of Information Management*, *10*(4), 1–10.

Falahati, S., Alizadeh, M., Ghazipour, F., Safahi, Z., Khaledian, N., and Salmanpour, M. R. (2025). An AI-powered Public Health Automated Kiosk System for Personalized Care: An Experimental Pilot Study. arXiv preprint arXiv:2504.13880.

Ireri, D. M., Awuor, M., Ogalo, J., and Nzuki, D. (2021). Role of ICT in the dissemination and access of agricultural information by smallholder farmers in South Eastern Kenya. *Acta Inform Malaysia*, *5*, 31-41.

Jeet, I., and Kumar, A. (2024). Community based agricultural extension models for accelerating technology adoption among small farmers. *Life Science Review*, 5(2): 45–52.

Lubell, M., Niles, M., and Hoffman, M. (2014). Extension 3.0: Managing agricultural knowledge systems in the network age. *Society and Natural Resources*, *27*(10), 1089-1103.

Martinez, L., Garritsen, K., Baguet, J., Grigolon, A., Münzel, K., Keserü, I., and Geurs, K. (2024). Digital kiosks and inclusivity: a novel perspective on mobility hubs. *European Transport Research Review*, *16*(1), 53.

Michael, O. N., and Ogunsola, O. E. (2021). Role of agricultural extension services in driving innovation adoption among rural farmers in emerging markets. *International Journal of Multidisciplinary Research and Growth Evaluation*, 1(2), 220–231.

Moon, S., Gim, J., Kim, C., Kim, Y., Kim, Y., and Choi, K. (2025). A Low-Code Methodology for Developing AI Kiosks: A Case Study with the DIZEST Platform. 2025 14th International Conference on Control, Automation and Information Sciences (ICCAIS), 87-91.

Mulungu, K., Kassie, M., and Tschopp, M. (2025). The role of information and communication technologies-based extension in agriculture: application, opportunities and challenges. *Information Technology for Development*, *31*(4), 1117-1146.

Ongachi, W., and Belinder, I. (2025). Agricultural extension as a pathway to livelihood diversification and sustainable development in rural communities: a systematic review. *BMC Agriculture*, *1*(1), 6.

Priya, N. K., Patil, S. S., Vishwakarma, S. K., Saikanth, D., Mishra, I., Tripathi, S., Pathak, A.K., and Shastri, S. (2025). Digital innovations in extension education: A review of emerging technologies and their impact on agricultural knowledge dissemination. *Journal of Experimental Agriculture International*, *47*(5), 408-423.

Qaisar, T. M., Khan, M. M. A., and Alom, S. (2011). Innovative agricultural information services by ICT projects in India. *International Journal of Trade, Economics and Finance*, *2*(4), 276-279.

Rajagopal, A., Rakshith, N. V., and Samarth Agasthya, M. S. (2021). A kiosk to provide information on government schemes to rural population and other services. In *2021 IEEE International Conference on Mobile Networks and Wireless Communications (ICMNWC)* (pp. 1-5).

Sangbuapuan, N., and Guha, S. (2016). Improving rice farming in Thailand using information kiosks. *Information Development*, *32*(5), 1372-1386.

Singh, R., Doharey, R. K., Meena, N. R., Singh, A., Singh, S., Singh, A. S., and Sudhanshu (2024). Accessibility and mass media utilization of extension personnel towards e-extension tools. *International Journal of Agriculture Extension and Social Development*, 7(5), 269-271.

Sarsale, C. J. C., and Osorno, R. D. (2025). Fast Food and Fast Ordering: The Digital Ordering Kiosk. *International Journal of Recent Advances in Multidisciplinary Topics*, 6(12), 34-43.

Sen, L. T. H., Phuong, L. T. H., Chou, P., Dacuyan, F. B., Nyberg, Y., and Wetterlind, J. (2025). The Opportunities and Barriers in Developing Interactive Digital Extension Services for Smallholder Farmers as a Pathway to Sustainable Agriculture: A Systematic Review. *Sustainability, 17*(7), 3007.

Sameer, S. (2023). Automated food ordering system. In: S., Sruthi (ed). *Emerging Trends in Commerce and Management*, Vol. 2. India, pp. 1-15.

Sharma, T., Anand, A., and Nair, P.S. (2017). Using kiosks as information-delivery channels to apply for schemes and other government services for rural India. *International Journal of Engineering and Computer Science*, 6(4): 21092–21097.

Sousa, F., Nicolay, G., and Home, R. (2016). Information technologies as a tool for agricultural extension and farmer-to-farmer exchange: Mobile-phone video use in Mali and Burkina Faso. *International Journal of Education and Development Using Information and Communication Technology, 12*(3), 19-36.

Steinke, J., Van Etten, J., Müller, A., Ortiz-Crespo, B., Van de Gevel, J., Silvestri, S. and Priebe, J. (2021). Tapping the full potential of the digital revolution for agricultural extension: an emerging innovation agenda. *International Journal of Agricultural Sustainability*, *19*(5-6), 549-565.

Subrahmanyam, T. V., Satish, K., and Viswanadham, Y. K. (2012). K-RIAD kiosk for rural India agricultural development – Farmer to e-farmer. *International Journal of Engineering Research and Technology (IJERT)*, *1*(6), 1-6.

Touri, M. (2021). Deconstructing the role of ICTs in agricultural development using the diverse economies framework. *Information Technology for Development, 27*(4), 690–713.

Vikas, K., Shashidhara, K.K., Reddy, B.S., and Goudappa, S.B. (2020). Usage of ICT tools for diffusion of agricultural information. *International Journal of Current Microbiology and Applied Sciences*, 9(7): 3712–3721.

Zhang, Y., Wang, L., and Duan, Y. (2016). Agricultural information dissemination using ICTs: A review and analysis of information dissemination models in China. *Information processing in agriculture*, *3*(1), 17-29.

AGRICULTURE BULLETIN
ISSN: 3049-2289

Recycling of sugarcane byproducts for enhancing soil productivity

Usha, N., Laxman Navi, and Karthik, A. N.
Department of Agronomy, University of Agricultural Sciences, GKVK, Bengaluru-560065

Sugarcane is an important commercial crop, and the sugar industry generates large quantities of byproducts such as pressmud, bagasse, bagasse ash, molasses and spent wash during sugar and ethanol production. Disposal of these residues often creates environmental and pollution problems. However, these byproducts are rich in organic matter and essential plant nutrients, making them valuable resources for improving soil fertility and crop productivity. Recycling sugarcane byproducts in agricultural fields can enhance soil physical, chemical and biological properties by increasing organic matter content, improving soil structure, enhancing microbial activity and promoting nutrient availability. Organic residues such as pressmud and bagasse ash act as soil amendments and nutrient sources, while spent wash can be used as a liquid fertilizer when applied at appropriate dilution levels. Utilization of these byproducts not only helps in waste management but also reduces dependence on chemical fertilizers and improves soil sustainability. Therefore, recycling sugarcane byproducts in agriculture provides an eco-friendly and cost-effective strategy for enhancing soil productivity and maintaining long-term soil health.

Introduction

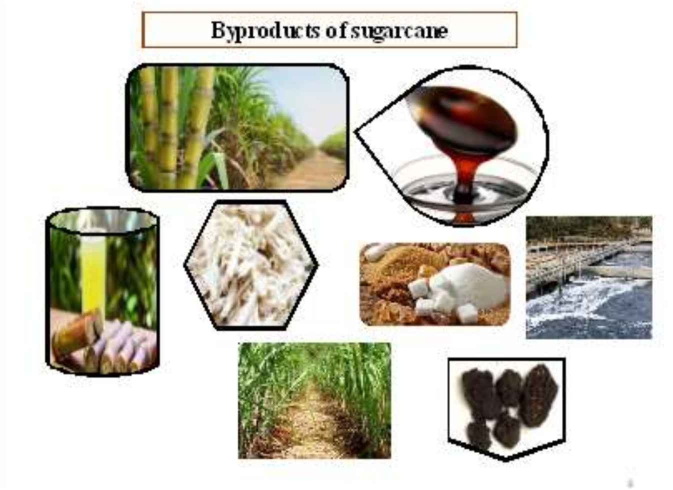
India is the largest consumer and second largest producer of sugar in the world after Brazil. The sugar industry is the second largest agro-processing industries in India next to textiles industry .Sugarcane crop is an important cash crop grown for the preparation of sugar and related products. The sugar industry is an agro-based industry that discharges different waste products during sugar and alcohol formation. These wastes, including SCB, BA, PMC, molasses, SCV, and SW, are produced in large amounts and their disposal causes environmental issues. Byproducts are organic and are rich in nutrients that were taken up by the crop. This property makes these organic wastes beneficial to be utilized in agriculture with no environmental hazards. The solid wastes can replace inorganic fertilizers, while distillery effluents can also solve the problem of water shortage. Sugar industries produce different organic byproducts that have a great potential to improve the soil's physical, chemical, and biological properties and crop productivity. It is recommended to use these organic byproducts along with mineral fertilizers to enhance the plant nutrient availability. Thus, it can contribute to minimizing the fertilizer shortage for heavy nutrient feeder crops such as sugarcane, maize etc

Pressmud is the compressed sugar industry waste produced from the filtration of the cane juice. Molasses is utilized in the distillery for the production of alcohol. The distilleries release a huge quantity of spent wash. These waste products cause disposal and pollution problems. Pressmud cake (PMC) is one such source of organic matter and nutrients (rich in potassium and phosphorus) which can be profitably utilized for crop production. PMC like other organic manures has great potential to supply nutrients in addition to its favourable effects on physico-chemical and biological properties of soil. The value of pressmud as an organic manure has been well recognized for utilizing in agriculture, as it contains valuable plant nutrients in organic form besides being a very effective soil ameliorant

Bagasse ash contains fewer nutrients, but it can also be utilized as fertilizer. All the wastes products have the potential to replace or minimize the use of mineral fertilizers along with the improvement of soil physical, chemical, and biological properties while PMC and SCV are good sources of plant nutrients and organic matter. Distillery SW can also be used as

ISSN: 3049-2289

fertilizer, but it should be diluted to certain levels to avoid heavy metal accumulation.



Byproducts of Sugarcane

- Juice
- Bagasse
- Trash
- Molasses
- Presmud
- Spentwash
- Vinasse

Fig. 01: Area, Production and Productivity of sugarcane in India

Source: Directorate of Economics and Statistics, Ministry of Agriculture & Farmers' Welfare, New Delhi

Table 01: Sugarcane byproducts produced by the sugar mills in India (m t)

States	Pressmud	Bagasse	Bagasse ash
Punjab	0.111	0.555	0.094
Haryana	0.160	0.801	0.136
Uttar Pradesh	3.516	17.571	2.987
Karnataka	0.913	4.566	0.773
Maharashtra	1.925	9.624	1.630
All India	8.774	43.843	7.454

Fertilizer Statistics, 2016

Among the different states, Uttar Pradesh accounts for higher byproduct generations like pressmud, bagasse and bagasse ash compared to other states

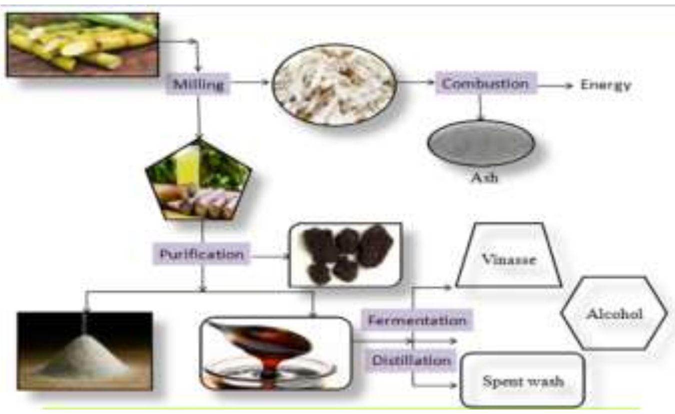


Fig.02: Flowchart of sugar and ethanol production process along with byproducts

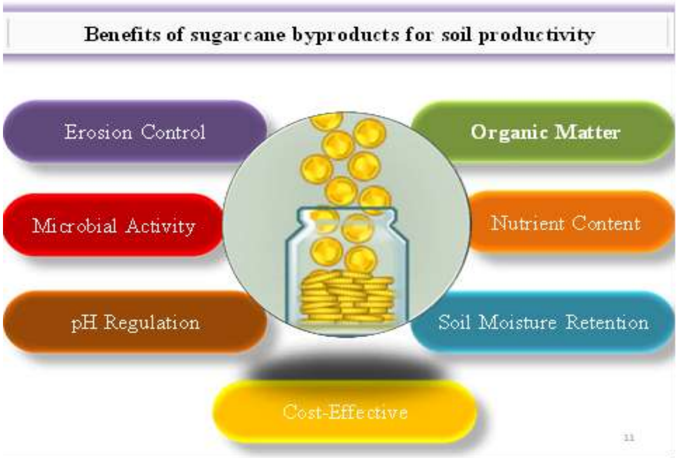
Raza *et al.*, 2021

Importance of Soil Productivity Enhancement

Why Enhancing Soil Productivity Matters?

- It enhances yield quantity and quality
- It promotes environmental sustainability and cost-effectiveness in the long term

- It ensures a resilient and profitable industry for both producers and the environment



Benefits of sugarcane byproducts for soil productivity

1. Organic Matter: Sugarcane byproducts like bagasse (fibrous residue) and molasses (a byproduct of sugarcane processing) add organic matter to the soil, improving its structure, water retention, and nutrient-holding capacity.

2. Nutrient Content: These byproducts are rich in nutrients such as nitrogen, phosphorus, potassium, and micronutrients. When incorporated into the soil, they release these nutrients slowly, providing a sustained source of nutrition for plants.

3. Soil Moisture Retention: The organic matter in sugarcane byproducts helps to improve soil structure, allowing it to retain moisture better. This is particularly beneficial in dry or arid regions where water retention is crucial for plant growth.

4. pH Regulation: Sugarcane byproducts can help regulate soil pH levels, making them more suitable for optimal plant growth. They can buffer acidic or alkaline soils, creating a more balanced environment for plant roots.

5. Microbial Activity: Sugarcane residues can enhance microbial activity in the soil. Beneficial soil microorganisms break down organic matter, releasing nutrients in forms that plants can readily absorb. This helps in nutrient cycling and overall soil health.

6. Erosion Control: By adding organic matter to the soil, sugarcane byproducts can help reduce soil erosion by improving soil structure and stability. This is especially important in sloping or vulnerable areas.

7. Cost-Effective: Utilizing sugarcane byproducts for soil improvement can be cost-effective for farmers since they are often readily available as a byproduct of sugarcane processing, reducing the need for expensive chemical fertilizers.

Conclusion

Sugarcane byproducts such as pressmud, bagasse, bagasse ash, molasses and spent wash possess significant potential for improving soil fertility and crop productivity. These materials are rich in organic matter and plant nutrients, which help improve soil structure, enhance microbial activity, increase nutrient availability and improve soil moisture retention. Recycling these residues in agricultural fields provides an environmentally sustainable approach to managing sugar industry wastes while simultaneously improving soil health. The combined use of sugarcane byproducts with inorganic fertilizers can further enhance nutrient use efficiency and crop performance. Therefore, effective utilization of sugarcane byproducts can play an important role in sustainable agriculture by reducing waste disposal problems, lowering fertilizer costs and enhancing long-term soil productivity.

Reference

ANONYMOUS. 2022,*Agricultural Research Data Book: Statistics at a Glance*. New Delhi: Directorate of Economics and Statistics, Ministry of Agriculture, Government of India.

Fertilizer statistics 2016, Fertilizer Association of India, New Delhi

Raza, Q. U. A., Bashir, M. A., Rehim, A., Sial, M. U., Ali Raza, H. M., Atif, H. M., And Geng, Y., 2021, Sugarcane industrial byproducts as challenges to environmental safety and their remedies: A review. *Water*, 13(24): 3495.

AGRICULTURE BULLETIN
ISSN: 3049-2289

Microgreen Revolution: From Nutrition to Business

[1*]Gokul Raj A and [2]Pankaj Kala
[1*]B.Sc. (Hons.) Horticulture Graduate, Horticultural College and Research Institute, TNAU, Paiyur - 635 112, Krishnagiri, Tamil Nadu, India.
[2]IV Year B.Sc. (Hons.) Horticulture, Horticultural College and Research Institute, TNAU, Periyakulam - 625 604, Theni, Tamil Nadu, India.

Microgreens cultivation is a booming agribusiness that captivates many agripreneurs. They are tiny leafy veggies packed with immense nutrients, containing 4-40% more than their mature counterparts. They require minimal space and low investment but yield high returns. They are more suitable for indoor and modern urban farming. They are usually harvested in 7-10 days and are available in various colours. The shelf life is a constant concern, but consuming them fresh is more efficient. Microgreens are consumed by top restaurants, cafes, and health-conscious individuals. They also have scope as space food. This article provides comprehensive information on Microgreens, from production to harvest and market trends.

Introduction

Agriculture is the backbone of the Indian Economy. Nowadays, the perspective on agriculture has changed from merely food production to a profitable business. The government also encourages the people who aspire to agribusiness by various means. Among all the agribusiness ventures, Microgreens Farming has earned a peculiar attention and it is rapidly growing in recent days. Unlike usual farming, it generally demands a smaller space, lesser inputs but offers greater prospects. Women Entrepreneurs are more interested in Microgreens Farming as they can be cultivated in homes itself. Also, it improves health as well as wealth. Here let's discuss the cultivation and marketing aspects of Microgreens - the miniature nutritional powerhouse.

Significance and Potential of Microgreens:

Microgreens are young vegetable plants harvested 7–21 days after germination. They are larger than sprouts, smaller than baby greens, and valued for their good flavour, colour, and high nutrient content. Microgreens like broccoli, radish, spinach, amaranth, coriander, basil, beetroot, and mustard are easy to grow and can be produced all year round. They need very little space and grow well on balconies, rooftops, or indoors, which makes them perfect for urban areas.

These young greens are a good source of vitamins, minerals, and antioxidants, often up to 4 to 40 percent more than their mature counterparts. Their fresh taste, high nutrition, and quick growth make microgreens popular among health-conscious people and small growers. From a business point of view, they need low investment, yield in a short time period, and have strong demand among health-conscious consumers. They also use less water and land, making microgreens a sustainable and promising option for future agribusiness and food security.

Difference Between Sprouts, Microgreens, and Baby Greens:

For a layman, sprouts, microgreens, and baby greens can be confusing because they look similar, but they actually belong to different growth stages of a plant, and have their own characteristics and uses.

Feature	Sprouts	Microgreens	Baby Greens
Harvest time	2–5 days	7–21 days	15–40 days
Plant parts eaten	Seed, root, stem	Stem + cotyledon + true leaves	Mature leaves
Growing medium	Water only	Soil / cocopeat /	Soil / cocopeat /

ISSN: 3049-2289

		hydroponics	hydroponics
Size	Very small	2–3 inches	3–4 inches
Nutritional value	Moderate	Very high	Lower than microgreens
Food safety risk (Risk of microbial contamination)	Higher 	Lower 	Lower 

Popular Microgreen Varieties and Colours:

Microgreens can be cultivated from a wide range of commonly consumed vegetables and grains, including cauliflower, broccoli, cabbage, radish, carrot, garlic, onion, amaranth, beetroot, spinach, cucumber, melon, and squash. Cereals like rice, wheat, oats, maize, and barley, as well as legumes such as chickpeas, beans, and lentils, are also used. Each variety exhibits distinct flavours, ranging from mild to spicy, sour, bitter, or peppery, depending on the species.

Microgreens are called as "Vegetable confetti" because they come in multiple colours associated and offer a variety of bioactive compounds with health benefits.

1. *Red microgreens*: contain lycopene, an antioxidant linked to cardiovascular support. (eg - Red amaranth, red cabbage, beetroot)
2. *Orange and yellow*: varieties are rich in carotenoids like beta-carotene and lutein, which contribute to vitamin A synthesis and visual health. (eg - Yellow mustard, sunflower, corn)
3. *Blue and purple microgreen*: contain anthocyanins that protect cells from oxidative damage. (eg - Purple radish, purple basil, kale)
4. *Green microgreens*: offer phytochemicals including indoles, saponins, and carotenoids, promoting general health. (eg - Fenugreek (methi), pea, coriander)
5. *White and brown microgreens*: it includes garlic and onion, contain allicin, noted for its antibacterial and immune-enhancing effects. (eg - Garlic, onion, leek)

Microgreens are easy to grow and can be produced at home or on a commercial scale. With basic control over light, water, and nutrients, they grow quickly and give fresh, clean produce, making them suitable for both daily use and business.

Level	Method	Medium / System	Key Points	Use
Home / Indoor	Tray-based (soil / soilless)	Coco peat, grow mats	Low cost, easy, no nutrients needed	Home use
Urban / Small Business	Rack & tray	Soilless + LED	Space-saving, uniform growth	Local sales
Semi-Commercial	Hydroponics	DWC / NFT	High yield, clean produce	Restaurants, markets
Commercial	CEA systems	Controlled climate	Year-round, consist	Large-scale business

			ent quality	
Advanced	Aeroponics / Aquaponics	Mist / Fish-water	High efficiency, sustainable	Premium production

Harvest and Storage:

As we discussed earlier, Microgreens are consumed in their early stages of growth. They are harvested after the emergence of the first set of true leaves. You should know that true leaves are different from cotyledon leaves. It takes 7 to 14 days after germination. At this stage, we can enjoy the best flavour, texture and nutritional content.

It is ideal to harvest during the morning as freshness can be maintained better. Before harvesting, sanitize yourself, the knife you use to cut and the trays in which you keep the produce. To harvest them, cut off the shoot portion above the soil surface. After harvest, wash them in the running water and allow them to dry in the tray. After drying, they are packed in glass or food grade plastic containers.

In some varieties like Pea Shoots, Wheatgrass second harvest is possible. To achieve this, cut them above 2-3 cm from the soil surface. It is best to consume the tiny greens soon after harvest. The shelf-life ranges for a week. Freezing might be done to store them for a long time but the quality won't be the same.

Market Demand, Supply Chain and Customer Behaviour:

- **Market Demand**

In India, microgreens are mostly demanded by hotels, cafes, cloud kitchens, and fitness centres in big cities. The general public still has limited exposure to microgreens.

- **Space farming**

Microgreens have short life cycle, need little space to grow and rich in nutrition due to this ability microgreens have great future potential in space farming. NASA (National Aeronautics and Space Administration) is doing research and testing them to provide fresh and nutritious food for astronauts. Microgreens health benefit and ease of cultivation make them ideal for future space farming.

Consumer Awareness

Most consumers do not clearly understand what microgreens are. Many confuse them with sprouts, which affects regular demand and market growth.

- **Supply Chain Issues**

Microgreens have a short shelf life and need quick delivery. Poor packaging and delayed transport often reduce freshness and quality.

- **Cold Chain Gap**

India lacks a proper cold-chain system for microgreens. Because of this, producers usually sell only in nearby areas.

- **Price Fluctuation**

Prices are unstable due to uneven demand and high production costs, making income uncertain for new growers.

- **Future Scope**

With rising health awareness and urban farming, microgreens have good future potential in India if awareness and supply systems improve.

Conclusion:

After the COVID-19 pandemic, the way people lead their lives has drastically changed. The fast-paced world now wants to slow down. People are becoming health-conscious and want to include organic foods and a balanced diet. Microgreens, being a wholesome nutritious food, top the diet list of health-conscious individuals. For those who aspire to enter the food or agri-business sector, this venture will be a promising one. Apart from this article, many workshops are available online and offline to dive into the world of Microgreens. Clearly, it's not only a business opportunity but also a catalyst for a healthy lifestyle. Micro Greens, Macro Wins!

Reference:

1. Divyanshi Rawat, Yachna Sood, Jyoti Devi, and Manmohan Lal. 2025. "Microgreens: Cultivation, Nutrition, Journey to Space and Market Trends". International Journal of Plant & Soil Science 37 (10):22–32. https://doi.org/10.9734/ijpss/2025/v37i105758.

2. Seth, T., Mishra, G. P., Sahu, A., Sarangi, S. K., Chandra, V., Dikshit, H. K., Chattopadhyay, A., Roy, P. D., Devi, M., Mhatre, C. S., Lyngdoh, Y. A., & Nair, R. M. (2023). Microgreens: Functional food for nutrition and dietary diversification. Journal of Food Science and Nutrition, Review Article, 1–15. (P:1-2&5-8)

3. Teng, Z., Luo, Y., Pearlstein, D. J., Wheeler, R. M., Johnson, C. M., Wang, Q., & Fonseca, J. M. (2021). Microgreens for home, commercial, and space farming: A comprehensive update of the most recent developments. Annual Review of Food Science and Technology, 12, 539–563. (P:7-10)

AGRICULTURE BULLETIN
ISSN: 3049-2289

The Tenure Dilemma: Rethinking Agricultural Research Management

BV Ramana Rao[1] and Surender Singh[2]
[1]Founder Project Coordinator, AICRP on Agricultural Meteorology
ICAR-CRIDA, Hyderabad, India
[2]Sr Professor/Principal Scientist (Rtd), Agricultural Meteorology
CCS Haryana Agricultural University, Hisar, India

Agricultural research is uniquely defined by its reliance on biological complexity and environmental unpredictability. Unlike controlled laboratory sciences, agricultural breakthroughs require validation across diverse soil types and fluctuating climates. To yield reliable, peer-reviewed outcomes, experiments must often span eight to ten years, capturing the full spectrum of inter-seasonal and intra-seasonal variability. This longitudinal approach is the bedrock of scientific integrity in the field. However, a systemic misalignment persists within the governance of these institutions. Leadership roles—including Directors, Vice-Chancellors, and national administrators—are typically governed by short-term mandates of three to five years. This creates a structural contradiction: the "Tenure Dilemma." While the science demands decade-long consistency, the leadership managing that science operates on a cycle too brief to oversee a project from inception to impact. This paper examines the implications of this disconnect, arguing that short administrative horizons incentivize "quick-fix" results over rigorous, long-term validation. Without addressing this temporal rift, agricultural research systems risk prioritizing administrative turnover over the sustainable, field-tested innovations essential for global food security.

1. Temporal Dimensions of Agricultural Research

The efficacy of agricultural innovation is inseparable from the passage of time. Unlike industrial or digital sectors where cycles move at the speed of silicon, agriculture is tethered to the rhythmic, often unpredictable, pace of the natural world. This temporal dependency is driven by three primary factors:

- **Climatic Variability**: Agriculture is an "open-air laboratory." Year-to-year fluctuations in rainfall, temperature extremes, and shifting humidity levels mean that a crop's performance in Year 1 may be entirely unrepresentative of its potential in Year 5. Robust data requires capturing these "inter-seasonal" anomalies to ensure a technology is resilient, not just lucky.
- **Biological Processes**: Soil health, nutrient cycling, and pest-pathogen evolutions are dynamic. For instance, the impact of a new fertilizer or tillage practice on soil organic matter may not be measurable for half a decade. Similarly, pest resistance often emerges over multiple generations, requiring long-term monitoring to validate sustainability.
- **Management Variability**: Farmers operate in diverse socio-economic and ecological niches. What works in a controlled research station may fail under varying farmer management practices.

Consequently, the gold standard for agricultural credibility rests on Long-Term Experiments (LTEs) and Farmer Participatory Testing. These methodologies ensure that a "breakthrough" is not merely a short-term spike, but a stable, reproducible solution. Short-term studies offer valuable snapshots, but only longitudinal validation provides the statistical confidence necessary to risk a farmer's livelihood on a new recommendation.

ISSN: 3049-2289

2.0 The Tenure Dilemma in Research Management

The "Tenure Dilemma" is a structural friction point where the slow, cumulative nature of biological discovery collisions with the fast-paced, high-visibility requirements of administrative office. While scientific breakthroughs are measured in decades, the success of a Director or Vice-Chancellor is often appraised in three-to-five-year cycles. This temporal misalignment forces a shift in institutional logic from persistence to perceptibility. When leaders operate under compressed timelines, they face immense pressure to demonstrate "impact" before their term expires. This often triggers three counterproductive tendencies:

- **Project Proliferation**: Launching "flagship" initiatives to secure a personal legacy, often at the expense of existing, long-term studies.
- **Priority Reorientation**: Shifting institutional focus toward trendy, short-cycle topics that yield quick data, sidelining foundational research like soil health or crop breeding.
- **Discontinuity**: New leadership frequently brings a "Year Zero" mentality, where ongoing programs lose funding or advocacy simply because they were inherited rather than initiated.

This constant churn creates a "start-stop" culture. Frequent transitions ensure that by the time a long-term experiment reaches its most critical data-yielding phase, the original administrative champion has moved on, leaving the project vulnerable to budget cuts or abandonment.

3. Implications for Research Systems

The structural misalignment between scientific necessity and administrative tenure doesn't just create friction; it fundamentally alters the output and integrity of agricultural research systems. When the governance of science becomes decoupled from the timeline of the natural world, four critical consequences emerge:

3.1 Fragmentation of Research Efforts: Research programs increasingly mirror the "projectized" nature of short-term leadership cycles. Instead of a cohesive, decade-long institutional strategy, the system becomes a collection of fragmented, three-year initiatives. This "siloed" approach prevents the accumulation of knowledge, as successive leaders pivot toward trendy but transient topics to secure quick institutional visibility.

3.2 Disruption of Long-Term Experiments (LTEs): LTEs are the crown jewels of agricultural science, providing data on soil health and climate resilience that cannot be replicated. However, under the "Tenure Dilemma," these trials are often viewed as budgetary burdens rather than assets. Without a long-term administrative champion, these experiments face neglect, modification, or mid-stream discontinuation, resulting in an irreparable loss of longitudinal data and historical insights.

3.3 Premature Technology Release: The pressure to deliver "measurable impact" within a single administrative term can lead to the dangerous fast-tracking of technologies. When seeds, chemicals, or management protocols are recommended after only two or three seasons of testing, they lack the "stress-testing" of climatic extremes. This shifts the risk of failure from the laboratory to the farmer's field, potentially eroding the hard-earned trust between the scientific community and rural stakeholders.

3.4 Erosion of Institutional Memory: Frequent leadership turnover creates a "Year Zero" culture. New administrations often lack the historical context of past failures or successes, leading to the "reinvention of the wheel." This weakening of institutional memory ensures that lessons learned a decade ago are forgotten, stifling the continuous, incremental learning that is essential for solving complex agricultural challenges.

4. Leadership Constraints and Systemic Limitations

It is critical to clarify that the "Tenure Dilemma" is not a failure of individual capability or professional integrity. Rather, it is a structural byproduct of how

ISSN: 3049-2289

agricultural research governance is designed. Even the most visionary and dedicated leaders find themselves operating within a framework that systematically disincentivizes long-term scientific stewardship in favor of immediate administrative benchmarks.

4.1 The Mandate Trap: Administrative roles are governed by rigid, time-bound mandates. When a Director or Vice-Chancellor is appointed for a three-to-five-year term, their performance is often evaluated based on "visible achievements"—new buildings, signed Memoranda of Understanding (MoUs), or the launching of high-profile "flagship" programs. In this environment, the quiet, painstaking work of maintaining a decadal soil fertility trial offers little in the way of immediate political or administrative capital.

4.2 Stakeholder and Resource Pressures: Leaders face constant pressure from funding agencies, government bodies, and social stakeholders to show "Return on Investment" (ROI). Because public and private funding cycles are increasingly tied to annual or biennial reviews, leaders are forced to prioritize short-cycle projects that produce "publishable" or "reportable" results quickly. This creates a survivalist logic where long-term continuity is sacrificed to meet current fiscal or political expectations.

4.3 The Expertise Gap and Genesis Blindness: A significant systemic limitation occurs when a new incumbent's domain expertise does not align with the specialized long-term projects they inherit. A leader may fail to grasp the historical "genesis" or the strategic longitudinal value of a specific multi-location trial if it falls outside their technical background. Without this inherent appreciation, these critical projects are often viewed as legacy overhead rather than scientific priorities. Consequently, the lack of "domain-sync" between leadership and ongoing research leads to a breakdown in institutional advocacy, further deepening the rift between administrative governance and scientific necessity.

5. Rethinking Leadership in Agricultural Research

To bridge the rift between scientific necessity and administrative cycles, we must move away from person-centric governance and toward system-oriented leadership. Addressing the tenure dilemma requires structural safeguards that ensure the institution's scientific mission outlives any single individual's appointment.

***5.1 Institutionalizing Continuity**:* Long-term research agendas must be decoupled from the personal preferences of changing leadership. By embedding these agendas into the core institutional charter, they become protected mandates rather than optional initiatives. This ensures that a strategic shift in "priority" requires rigorous peer justification rather than a simple administrative decree.

5.2 Protecting Long-Term Experiments (LTEs) as National Assets: Critical, long-duration trials should be formally designated as National Scientific Assets. This status would provide them with "ring-fenced" funding and oversight committees that remain stable regardless of transitions at the Director or Vice-Chancellor level. Treating these trials as heritage infrastructure ensures that decades of data are not lost to short-term budgetary or administrative pivots.

5.3 Redefining Performance Metrics: We must redefine what "success" looks like for a research leader. Current metrics favor visible, short-term outputs. A more sustainable framework would evaluate leadership based on:

- **System Strengthening**: How well they fortified the institution's infrastructure and human capital.
- **Continuity Assurance**: Their success in advancing inherited long-term projects toward their logical conclusion.
- **Legacy Impact**: Prioritizing foundational progress over "vanity metrics" and quick-release technologies.

5.4 Collective and Distributed Leadership: Relying on a single "apex" leader often invites discontinuity. Shifting toward a collective leadership model—where multi-institutional partnerships and expert committees hold decision-making power—distributes ownership. This mitigates the risk of "ego-driven" disruptions, where a new incumbent might hesitate to support collaborative ventures they did not personally initiate. By fostering a culture of shared stewardship, we ensure that partnerships and research programs maintain their momentum across leadership transitions.

6. Leadership Strategies Within Short Tenures

The inherent limitations of a short tenure do not preclude a leader from leaving a profound legacy. However, achieving this requires a fundamental shift in perspective: the leader must transition from being a "driver of change" to a "custodian of progress." Success in a three-to-five-year window is best measured not by the new projects initiated, but by the resilience and maturity of the systems left behind.

6.1 The Stewardship Model: Effective leaders within short tenures prioritize the health of ongoing programs. By acting as a custodian, a leader ensures that long-term experiments are adequately funded and shielded from external pressures. This involves strengthening institutional documentation and data management systems, ensuring that every byte of research data is preserved in a way that is accessible to future administrations. This "knowledge-first" approach prevents the erosion of institutional memory and ensures that scientific value accumulates across leadership cycles.

6.2 Building Human and Physical Capital: Lasting value is often found in the "scaffolding" of science. Investing in advanced infrastructure—labs, sensor networks, and automated data repositories—provides a foundation that benefits the institution for decades. Simultaneously, focusing on building strong, autonomous scientific teams reduces the system's reliance on the individual at the top. When excellence is distributed across a department or a collaborative network, the research remains steady even when the leadership chair changes.

6.3 The Risk of the Personal Agenda: A critical danger arises when a personal agenda dominates the institutional mission. If a leader prioritizes "vanity projects" or short-term "metrics of visibility" to enhance their own post-tenure prospects, the system risks derailment. Once an institutional culture shifts from scientific rigor to administrative signaling, the damage is difficult to reverse. Realigning a derailed system—where ego has superseded collaborative ethics—can take years of corrective governance. Therefore, the most impactful leaders are those who seek to be "invisible" facilitators, ensuring the institution’s trajectory remains fixed on long-term impact rather than short-term acclaim.

7. Policy Implications: The Case of ICAR Leadership

At the apex of India’s agricultural research architecture, the tenure dilemma takes on national significance. The Director General (DG) of the Indian Council of Agricultural Research (ICAR) is not merely an administrator but the primary architect of the country’s food security and climate resilience strategies. However, when this pivotal role is restricted to a short tenure—often around three years—the misalignment between administrative cycles and scientific timelines reaches a critical breaking point.

7.1 The Constraint of Brief Mandates: A three-year window is fundamentally insufficient for a leader to oversee the "concept-to-crop" cycle. Within such a limited duration, a DG is severely constrained in their ability to:

- **Conceptualize and Implement**: Launching a national-level mission, such as a multi-state soil health program or a climate-smart breeding initiative, requires years of planning and pilot testing before full-scale deployment.
- **Ensure Continuity**: National programs involving hundreds of constituent

laboratories require a steady hand to maintain momentum. Frequent transitions at the top often lead to "policy drift," where long-term objectives are sidelined by the immediate pressures of a new incumbent's short-term targets.

7.2 The Case for Decadal Leadership: Given that reliable agricultural outcomes require eight to ten years of validation, leadership at the national level must be recalibrated to match these scientific realities. It is proposed that candidates for top research management positions be selected based on their potential to contribute for a minimum of 8–10 years. This could be achieved either through extended single tenures or a structured path of leadership continuity. A decadal horizon would empower the DG to move beyond "patchwork" solutions and instead build institutional coherence. By aligning the leadership cycle with the biological cycle of the field, the ICAR can ensure that its policy direction is as resilient and sustainable as the crops it seeks to develop.

8. Towards a Continuity-Centric Research System

The ultimate objective of reform is to transition from a tenure-driven system to a continuity-driven one. This shift recognizes that while individual leaders are temporary, the institutional mission is perpetual. To bridge the structural gap between administrative and scientific timelines, the following pillars of a continuity-centric system are proposed:

- **Synchronization of Mandates**: Leadership tenures, particularly at the national and institutional levels, must be recalibrated to reflect the biological reality of agricultural cycles. Aligning these mandates with a minimum eight-to-ten-year horizon allows a leader to move beyond the "initiation phase" and into the "impact phase" of research.
- **Structured Succession Planning**: To mitigate the "Year Zero" culture, succession must be a deliberate, multi-year process. Incoming leaders should be integrated into ongoing long-term strategies well before assuming full authority, ensuring that the "genesis" of critical projects is preserved and understood.
- **Independent Oversight and "Ring-Fenced" Funding**: Long-term experiments (LTEs) and multi-decadal soil health programs should be governed by independent scientific boards that transcend individual tenures. Coupled with dedicated, non-lapsable funding mechanisms, these "national assets" can be shielded from the shifting priorities or personal agendas of changing administrations.

By institutionalizing these measures, agricultural research management can finally align its governance with the natural variability it seeks to master. A continuity-centric system ensures that the path from the laboratory to the farmer's field remains stable, evidence-based, and resilient against the disruptions of administrative turnover. To refine the accountability mechanism within the proposed long-tenure model, the timing and transparency of the evaluation must be precise. Adding these specific parameters ensures that the system remains meritocratic without creating prolonged administrative uncertainty. Here is the updated conclusion incorporating your specific timeline for the external review:

9. Vision Beyond

The "Tenure Dilemma" represents a fundamental structural misalignment that threatens the scientific integrity of agricultural research. While the natural world—governed by climatic variability and biological evolution—demands decades of patient observation, our current governance systems often operate on fragmented, short-term cycles. This discordance compromises the reliability of research outcomes and, ultimately, the livelihoods of the farmers who depend on them. Bridging this gap requires a profound paradigm shift. We must move away from evaluating leadership based on the "newness" of initiatives and instead value the stewardship and completion of long-term scientific

ISSN: 3049-2289

missions. Agricultural leadership must be redefined as a relay, where the success of one tenure is measured by the momentum it provides to the next.

To operationalize this, a new model of high-level recruitment is essential. While extending tenures to eight or ten years provides the necessary scientific horizon, it must be balanced with rigorous, early-stage accountability. It is proposed that such appointments be subject to a mandatory external review completed within 23 months of the initial appointment. To maintain professional standards and institutional stability, the leader should be provided with one month's formal notice prior to the commencement of this evaluation. To ensure absolute objectivity and eliminate institutional bias or "ego-driven" protections, this review committee must be comprised entirely of external experts with no representatives from within the organization. This 24-month threshold serves as a critical "go/no-go" point, allowing for the early curtailment of inefficiency while granting high-performing, visionary leaders the long-term stability required to see decadal research through to its final impact phase.

AGRICULTURE BULLETIN
ISSN: 3049-2289

Science in Silos: Agricultural Meteorology Seeking Relevance in Indian Agriculture

BV Ramana Rao[1] and Surender Singh[2]
[1]Founder Project Coordinator, AICRP on Agricultural Meteorology
ICAR-CRIDA, Hyderabad, India
[2]Sr Professor/Principal Scientist (Rtd), Agricultural Meteorology
CCS Haryana Agricultural University, Hisar, India

Agricultural Meteorology, as an interdisciplinary science, plays a crucial role in understanding the complex interactions between weather, climate and agricultural production systems. In a country like India, where agriculture is highly sensitive to climatic variability, the discipline holds immense potential to guide sustainable and resilient farming practices. However, despite its scientific relevance and strategic importance, Agricultural Meteorology continues to function in relative isolation from mainstream agricultural research, policy formulation, and field-level decision-making. This article critically examines the factors contributing to the marginalization of Agricultural Meteorology in India, analyzes the consequences of its institutional and functional isolation, and proposes pathways to reposition the discipline as a central pillar of agricultural development in the era of climate change.

1. Introduction

Agriculture in India is intrinsically linked to weather and climate. The success or failure of crops often depends not merely on genetic potential or agronomic practices, but on the variability and predictability of atmospheric conditions. Agricultural Meteorology, which integrates meteorological data with agricultural science, is uniquely positioned to provide insights that can enhance productivity, reduce risks, and improve resource use efficiency. Despite this inherent importance, Agricultural Meteorology has not achieved the centrality it deserves within the agricultural research and development ecosystem. It often operates at the margins of institutional structures, academic curricula, and policy frameworks. This paradox—where a highly relevant science remains underutilized—raises important questions about the organization, governance, and priorities of agricultural research in India. The notion that Agricultural Meteorology is evolving as a "science in solitude" reflects not a lack of scientific progress, but a systemic disconnect between knowledge generation and its application. Understanding this disconnect is essential for strengthening the role of the discipline in addressing contemporary challenges such as climate change, resource degradation, and livelihood insecurity.

2. Conceptual Foundations of Agricultural Meteorology

Agricultural Meteorology is fundamentally an applied science that seeks to interpret atmospheric processes in the context of agricultural systems. It encompasses the study of weather elements such as temperature, rainfall, humidity, wind, and solar radiation, and their influence on crop growth, soil processes, pest dynamics, and farm operations. The discipline extends beyond observation and analysis to include forecasting, modeling, and advisory services. It plays a critical role in determining sowing windows, irrigation scheduling, pest and disease management, and harvest planning. In recent decades, it has also become central to climate risk assessment and the development of climate-resilient agricultural strategies. Globally, Agricultural Meteorology has evolved as an integrative science, closely linked with disciplines such as agronomy, hydrology, remote sensing, and climate science. In India, however, its integration with these domains has been uneven, leading to its relative isolation.

3. Institutional Landscape in India

The development of Agricultural Meteorology in India has been shaped by institutions such as the and the . These organizations have made significant contributions in terms of establishing observatories, developing weather-based advisory services, and supporting research initiatives. However, the institutional arrangement has also contributed to fragmentation. Agricultural Meteorology exists at the intersection of two distinct systems: agricultural research and meteorological services. This dual positioning has resulted in ambiguity regarding ownership, accountability, and strategic direction. Within agricultural universities, the discipline is often treated as a specialized subject rather than a foundational component of agricultural science. In meteorological institutions, the focus tends to remain on weather prediction and atmospheric science, with limited emphasis on agricultural applications. As a result, Agricultural Meteorology does not fully belong to either system, reinforcing its status as a science in isolation.

4. Factors Contributing to Isolation

The isolation of Agricultural Meteorology in India can be attributed to a combination of structural, academic, and operational factors. One of the primary reasons is the lack of integration with core agricultural disciplines. Research programs in agronomy, plant breeding, and soil science frequently proceed without systematically incorporating weather and climate considerations. While meteorological data may be used retrospectively for analysis, it is rarely embedded proactively in experimental design or decision-making processes. Another contributing factor is the limited visibility of Agricultural Meteorology in policy frameworks. Although climate change has brought renewed attention to weather-related risks, the discipline itself is not explicitly recognized as a strategic driver in many national agricultural policies. This lack of policy emphasis translates into inadequate funding, limited human resource development, and weak institutional support.

Communication barriers further exacerbate the problem. The translation of scientific insights into actionable advisories for farmers remains a challenge. Issues related to language, accessibility, and trust hinder the effective dissemination and adoption of agrometeorological information. Consequently, even well-developed advisory systems fail to achieve their intended impact. The short tenure of leadership positions in agricultural research institutions also plays a role. Leaders with limited tenure often prioritize short-term, visible outcomes over long-term, integrative research approaches. Agricultural Meteorology, which requires sustained observations and longitudinal studies, does not align well with such short-term priorities.

5. Consequences of Scientific Isolation

The marginalization of Agricultural Meteorology has significant implications for agricultural productivity, sustainability, and resilience. At the farm level, the absence of timely and reliable weather-based decision support leads to suboptimal management practices. Farmers may miss critical sowing windows, apply inputs inefficiently, or fail to anticipate pest and disease outbreaks. This not only affects yields but also increases production costs and environmental risks.

At the research level, the lack of integration results in incomplete understanding of crop performance. Experimental results that do not adequately account for weather variability may lead to recommendations that are not robust across different climatic conditions. This undermines the credibility and applicability of agricultural research. From a policy perspective, the underutilization of Agricultural Meteorology limits the effectiveness of interventions aimed at climate adaptation and risk management. Programs related to crop insurance, drought mitigation, and disaster preparedness could benefit significantly from the incorporation of agrometeorological insights. More broadly, the isolation of the discipline represents a missed opportunity to harness a science that is inherently suited to addressing the challenges of climate variability and change.

6. Emerging Relevance in the Context of Climate Change

The growing recognition of climate change as a major threat to agricultural systems has brought Agricultural Meteorology back into focus. Increasing frequency of extreme weather events, shifting rainfall patterns, and rising temperatures are compelling policymakers and researchers to seek solutions that are informed by climate science. Agricultural Meteorology provides the tools and frameworks needed to understand and respond to these changes. It enables the development of climate-resilient cropping systems, supports early warning systems, and facilitates adaptive management practices.

Advances in technology are further enhancing the potential of the discipline. Remote sensing, geographic information systems, and artificial intelligence are enabling more accurate and localized weather predictions. Mobile-based platforms are improving the dissemination of advisories to farmers. These developments create new opportunities to integrate Agricultural Meteorology into mainstream agricultural practices. However, realizing this potential requires a shift from viewing the discipline as a support service to recognizing it as a central component of agricultural innovation.

7. Pathways for Integration and Mainstreaming

Repositioning Agricultural Meteorology from a science in solitude to a science in leadership requires systemic changes at multiple levels. Institutionally, there is a need to strengthen collaboration between agricultural and meteorological organizations. Joint programs, shared data platforms, and coordinated research initiatives can help bridge existing gaps. Establishing dedicated centers for Agricultural Meteorology with clear mandates and adequate resources can provide the necessary focus and direction. Academically, the discipline should be integrated into the core curriculum of agricultural education. Training programs should emphasize interdisciplinary approaches, equipping students with the skills needed to apply meteorological knowledge in agricultural contexts. Capacity building should also extend to extension workers and farmers, ensuring that agrometeorological information is effectively utilized at the field level.

From a policy perspective, Agricultural Meteorology should be explicitly incorporated into national and state-level agricultural strategies. This includes aligning it with programs related to climate change, water management, and digital agriculture. Long-term research funding should be prioritized to support sustained observations and model development. At the operational level, efforts should focus on improving the relevance and usability of agrometeorological advisories. This involves tailoring information to local conditions, using regional languages, and leveraging digital technologies for dissemination. Building trust among farmers is critical, and this can be achieved through consistent and reliable service delivery.

8. Leadership and the Tenure Challenge

An important but often overlooked aspect of the problem is the mismatch between the time horizons of Agricultural Meteorology and the tenure of leadership in research institutions. The discipline relies on long-term data and sustained research efforts, often spanning decades. In contrast, leadership positions are frequently limited to short tenures, typically three to five years.

This mismatch discourages investment in long-term research programs and favors projects that yield immediate results. To address this issue, it is essential to ensure continuity in research leadership and to prioritize long-term institutional goals over short-term achievements. Appointments to key leadership positions should consider the need for sustained engagement with complex, interdisciplinary challenges.

9. Integrative Reflections

Agricultural Meteorology in India stands at a critical juncture. It has the scientific foundation, institutional presence, and technological support needed to play a transformative role in agriculture. Yet, its potential remains underutilized due to systemic isolation and lack of integration. The characterization of Agricultural Meteorology as a "science in solitude" is both a diagnosis and a call to action. It highlights the need to rethink how the discipline is positioned within the broader agricultural ecosystem.

Breaking this solitude requires more than incremental changes. It demands a paradigm shift that recognizes Agricultural Meteorology as a central, integrative science capable of guiding agriculture through the uncertainties of climate variability and change. In an era where the future of agriculture is increasingly uncertain, the integration of weather and climate intelligence into decision-making is not a luxury but a necessity. Agricultural Meteorology must move from the margins to the mainstream, from isolation to integration, and from support to leadership. Only then can it fulfill its true potential as a science that not only understands nature but also helps agriculture thrive in harmony with it.

AGRICULTURE BULLETIN
ISSN: 3049-2289

Catalyzing Agribusiness Startups: Role of Government Initiatives

Jyoti[1*], Dr. Suman Ghalawat[2], Karishma[3] and Bharat[4]
[1*,3]Research Scholar, [2] Associate Professor,[4]MBA
[1,2,3,4]Department of Business Management
COA, CCS Haryana Agricultural University, Hisar, Haryana, India

Agribusiness startups are emerging as a dynamic force in transforming Indian agriculture by promoting innovation, value addition, and employment generation. Recognizing their potential, the government has introduced several initiatives aimed at fostering entrepreneurship in the agricultural sector. This article explores the effect of these government initiatives on the growth and sustainability of agribusiness startups in India. It highlights key schemes related to finance, infrastructure, incubation, and digital agriculture, while also examining their influence on entrepreneurial motivation and business performance. The discussion further identifies critical challenges such as limited awareness, bureaucratic constraints, and uneven accessibility that hinder the effective implementation of these initiatives. The article concludes that although government support has significantly accelerated the emergence of agribusiness startups, there is a need for improved coordination, simplification of processes, and sustained support to ensure long-term success and rural economic transformation.

Introduction

Indian agriculture is undergoing a gradual but significant transformation, moving beyond traditional farming practices towards a more diversified and enterprise-driven system. At the center of this transformation lies the rise of agribusiness startups, which are integrating technology, innovation, and market-oriented approaches into agriculture. These startups are not only enhancing productivity but also addressing critical challenges such as post-harvest losses, inefficient supply chains, and limited market access.

In recent years, entrepreneurship in agriculture has gained momentum, particularly among educated youth and agriculture graduates. This shift has been largely influenced by supportive policy measures and targeted government interventions designed to promote agribusiness development. The Government of India has recognized the need to modernize agriculture and create employment opportunities in rural areas, leading to the introduction of various schemes and programs aimed at encouraging agribusiness startups.

These initiatives focus on reducing entry barriers, providing financial assistance, strengthening infrastructure, and offering training and incubation support. While the intent and design of these policies are commendable, their actual impact on the ground varies considerably. Understanding how these initiatives influence startup creation, growth, and sustainability is essential for improving policy outcomes and strengthening the agribusiness ecosystem.

Government Initiatives and Their Role in Agribusiness Development

- Government initiatives have played a foundational role in shaping the agribusiness startup landscape in India. One of the most significant contributions has been in improving access to finance, which is often cited as the biggest hurdle for new entrepreneurs. Schemes such as the Startup India Seed Fund Scheme and the Agriculture Infrastructure Fund have made it easier for startups to secure funding, particularly during the early stages of business development. By providing grants, subsidies, and credit guarantees, these programs reduce

ISSN: 3049-2289

financial risk and encourage individuals to venture into agribusiness.

- In addition to financial support, infrastructure development has been another critical area of intervention. The establishment of cold storage facilities, food processing units, and logistics networks has improved the efficiency of agricultural value chains. Programs like the Pradhan Mantri Formalisation of Micro Food Processing Enterprises (PMFME) have facilitated the growth of small-scale processing units, enabling entrepreneurs to add value to agricultural produce and access new markets.
- Equally important is the role of incubation and capacity-building initiatives. Programs such as RKVY-RAFTAAR have provided aspiring entrepreneurs with access to mentorship, technical expertise, and business development support. These incubation centers, often located within agricultural universities and research institutions, serve as hubs of innovation, helping startups refine their ideas and develop viable business models.
- Digital initiatives have further strengthened the agribusiness ecosystem by enabling data-driven decision-making and improving service delivery. Platforms aimed at integrating agricultural data and providing digital services to farmers have created new opportunities for startups to develop innovative solutions in areas such as precision farming, supply chain management, and financial services.

Impact on Agribusiness Startups

- The cumulative effect of these government initiatives has been a noticeable increase in the number of agribusiness startups across the country. Financial incentives and supportive policies have encouraged individuals, particularly youth, to consider entrepreneurship as a viable career option. This shift is significant in a country where agriculture has traditionally been associated with subsistence rather than enterprise.
- Government support has also facilitated the adoption of modern technologies in agriculture. Startups are increasingly leveraging tools such as mobile applications, data analytics, and automation to enhance productivity and efficiency. This technological integration has not only improved farm-level outcomes but also created new business opportunities in areas such as agri-logistics, input delivery, and market linkage services.
- Another important impact is the generation of employment opportunities in rural areas. Agribusiness startups contribute to job creation across various segments, including production, processing, marketing, and service delivery. By creating local employment opportunities, these enterprises help reduce rural-urban migration and promote balanced regional development.
- Furthermore, government initiatives have strengthened agricultural value chains by improving infrastructure and market access. Startups play a crucial role in connecting farmers to markets, ensuring better price realization and reducing inefficiencies in the supply chain. This has a direct positive impact on farmers' income and overall agricultural sustainability.

Challenges in Implementation

- Despite the positive impact, several challenges continue to limit the effectiveness of government initiatives. One of the most significant issues is the lack of awareness among potential beneficiaries. Many aspiring entrepreneurs are either unaware of available schemes or lack detailed knowledge about their eligibility criteria and application processes.
- Bureaucratic complexities also pose a major challenge. Lengthy procedures, documentation requirements, and delays in approvals can discourage entrepreneurs from applying for government support. In some cases, delays in fund disbursement can disrupt business operations and affect startup viability.

- Access to credit remains another persistent issue, particularly for first-generation entrepreneurs who lack collateral or credit history. While government schemes aim to address this problem, the gap between policy provisions and actual implementation often limits their effectiveness.
- Regional disparities further complicate the situation. The availability and effectiveness of government support vary across regions due to differences in infrastructure, institutional capacity, and administrative efficiency. Entrepreneurs in remote or underdeveloped areas often face greater challenges in accessing scheme benefits.
- Additionally, most government initiatives focus on the initial stages of startup development, with limited emphasis on long-term support. Startups often struggle to scale their operations due to lack of continued financial assistance, mentorship, and market access.

The Way Forward

- To enhance the effectiveness of government initiatives, a more integrated and inclusive approach is required. Simplifying application procedures and reducing bureaucratic hurdles can significantly improve accessibility. Digital platforms can be leveraged to streamline processes, improve transparency, and ensure timely delivery of benefits.
- Awareness campaigns should be strengthened to reach a wider audience, particularly in rural areas. Agricultural universities, extension services, and local institutions can play a key role in disseminating information and guiding entrepreneurs through the application process.
- Improving access to credit is also essential. Innovative financing models, such as collateral-free loans and venture capital funding, can help address the financial needs of startups. Strengthening partnerships between government agencies, financial institutions, and private investors can further enhance funding opportunities.
- Finally, there is a need for continuous support mechanisms that go beyond the initial stages of business development. Providing ongoing mentorship, market access, and technical assistance can help startups achieve long-term sustainability and growth.

Conclusion

Government initiatives have played a transformative role in promoting agribusiness startups in India. By addressing key barriers such as finance, infrastructure, and technical knowledge, these initiatives have created a supportive environment for entrepreneurship in the agricultural sector. The rise of agribusiness startups has contributed to innovation, employment generation, and improved agricultural productivity. However, the effectiveness of these initiatives is influenced by factors such as awareness, accessibility, and implementation efficiency. While significant progress has been made, challenges related to bureaucracy, regional disparities, and lack of sustained support continue to hinder their full potential. A more holistic approach that emphasizes simplification, coordination, and continuous support is essential for maximizing the impact of government initiatives. Strengthening the agribusiness ecosystem will not only enhance startup success but also contribute to sustainable agricultural development and rural prosperity.

References

Government of India. (2020). *Agriculture Infrastructure Fund: Operational Guidelines*. Ministry of Agriculture and Farmers Welfare.

Government of India. (2020). *Pradhan Mantri Formalisation of Micro Food Processing Enterprises (PMFME) Scheme Guidelines*. Ministry of Food Processing Industries.

Government of India. (2021). *Startup India Seed Fund Scheme*. Department for Promotion of Industry and Internal Trade.

ISSN: 3049-2289

NABARD. (2022). *NABVENTURES: Supporting Agri Startups in India*. National Bank for Agriculture and Rural Development.

Ministry of Agriculture and Farmers Welfare. (2021). *RKVY-RAFTAAR Scheme for Agripreneurship Development*.

Birthal, P. S., & Joshi, P. K. (2019). Agricultural diversification and market development in India. *Agricultural Economics Research Review*, 32(1), 1–12.

Kumar, A., Singh, R., & Sharma, P. (2020). Role of agribusiness entrepreneurship in rural development. *Indian Journal of Agricultural Economics*, 75(3), 345–356.

World Bank. (2020). *Transforming Agriculture for Inclusive Growth in South Asia*. World Bank Publications.

Food and Agriculture Organization (FAO). (2017). *Agribusiness and Value Chain Development*. FAO, Rome.

Singh, S., & Kaur, P. (2021). Government policies and agripreneurship development in India. *Journal of Agribusiness in Developing Economies*, 11(4), 567–582

ISSN: 3049-2289

Nano Fertilizers in Modern Agriculture

Subham Dutta[1]*, Moumita Roy[2], Koushik Ghosh[3], Saumyadip Chakraborty[4]

[1]Ph.D. Research Scholar, Department of Agronomy, Uttar Banga Krishi Viswavidyalaya, Pundibari, Coochbehar, West Bengal-736165

[2]Ph.D. Scholar, Department of Agronomy, Palli Siksha Bhavana (Institute of Agriculture), Visva Bharati University, Sriniketan, Bolpur, West Bengal, 731236,

[3]Ph. D. Research Scholar, Department of Soil Science and Agricultural Chemistry, Uttar Banga Krishi Viswavidyalaya, Pundibari, Coochbehar, West Bengal-736165

[4]Ph.D. Research Scholar, Department of Agricultural Extension, Uttar Banga Krishi Viswavidyalaya, Pundibari, Coochbehar, West Bengal-736165

Nano fertilizers are a new innovation in modern agriculture, which promises to increase nutrient use efficiency and support sustainable agriculture. The new fertilizers have been synthesized by utilizing nanotechnology, which ensures the release of nutrients in nanoscale forms to support plant growth. Compared to conventional fertilizers, nano fertilizers minimize nutrient loss by leaching, volatilization, and runoff, which in turn reduces environmental pollution. The new fertilizers support plant growth, increase yields, and improve stress tolerance while reducing the application rates. Despite the promising results, some concerns have been raised over the cost, scale, and environmental impacts. In conclusion, nano fertilizers have the potential to support precision and climate-resilient agriculture.

1.Introduction

The current agricultural system faces many challenges, including a growing rate of population, declining soil fertility, reducing arable land, and the negative impacts of climate change. These challenges require a high rate of crop productivity in a sustainable manner. Conventional chemical fertilizers have been instrumental in enhancing agricultural productivity. Despite their significance, their efficiency is relatively low, as only 30-50% of the applied fertilizer can be used by crops. The unused fertilizer is lost through leaching, volatilization, and surface runoff, causing soil degradation, water pollution, and global warming.

In order to address the challenges of conventional chemical fertilizers, new technologies have been explored in order to enhance fertilizer use in crops. Among the new technologies, nano technology has been identified as a promising technology. Nano technology involves the use of particles at a nano scale, i.e., between 1 and 100 nm. Nano fertilizers have been identified as a new innovative fertilizer derived from nano technology. Nano fertilizers enhance fertilizer use in crops, thus reducing fertilizer losses and promoting a sustainable agricultural system.

2. Definition of Nano Fertilizers

Nano fertilizers are an advanced technology in plant nutrition where essential plant nutrients are formulated at the nanoscale (1 to 100 nm) or encapsulated in nanostructures. This technology facilitates the slow and controlled release of plant nutrients to ensure efficient use by plants. Nano fertilizers are very small in size and thus interact more with plant cells to ensure efficient absorption and utilization by plants.

In simpler words:

Nano fertilizers are those fertilizers that provide plant nutrients in nano form to ensure efficient use and minimize losses to the environment.

3. Characteristics of Nano Fertilizers

Nano fertilizers have some specific characteristics which enable them to be highly efficient and environmentally sustainable.

ISSN: 3049-2289

- High Surface Area: The size of nano fertilizers is very small, which enables them to have a higher surface area, thus enhancing their interaction with plant tissues.
- Controlled and Slow Release: The nutrients in nano fertilizers are released gradually, thus ensuring plants receive nutrients over a long period.
- High Nutrient Use Efficiency: The proportion of nutrients in nano fertilizers is utilized by plants, thus reducing nutrient wastage.
- Targeted Action: The nutrients in nano fertilizers are released to specific parts of the plants, thus enhancing their efficiency.
- Eco-Friendly: The use of nano fertilizers ensures environmental sustainability since they reduce environmental pollution, minimize nutrient wastage, and reduce greenhouse gases.

4. Types of Nano Fertilizers

Nano fertilizers can be differentiated on the basis of the type of nutrients they deliver to the plants and the way they are formulated. These advanced fertilizers help in enhancing the availability and efficiency of uptake.

4.1 Nano Nitrogen Fertilizers

Nano nitrogen fertilizers, such as Nano Urea, are one of the most commonly used nano fertilizers. These fertilizers help in delivering nitrogen to the plants in the nano form. This nano form of nitrogen gets easily absorbed by the leaves when they are sprayed. Due to their high reactivity, nano nitrogen fertilizers get easily absorbed by the plants. This way, the efficiency of using these fertilizers is enhanced. With the help of nano nitrogen fertilizers, the same yield can be obtained with a smaller quantity of nitrogen. This way, the chances of loss are minimized.4.2 Nano Phosphorus Fertilizers

Phosphorus is often immobilized in soil due to fixation, making it less available to plants. Nano phosphorus fertilizers overcome this limitation by enhancing the solubility and mobility of phosphorus in the soil. These nano-formulations facilitate better root uptake and improve phosphorus availability even in soils with high fixation capacity. They support root development, energy transfer, and overall plant growth, thereby improving crop productivity.

Source: https://agribusinessedu.com/

4.3 Nano Potassium Fertilizers

Nano potassium fertilizers have a significant role to play in the regulation of plant physiological processes. Potassium in nano form is easily absorbed by plants. This helps in the improvement of drought and disease tolerance in plants. This type of fertilizer also helps in the improvement of the quality of crop produce.

4.4 Nano Micronutrients

Micronutrients such as zinc (Zn), iron (Fe), copper (Cu), and manganese (Mn) play a significant role in plant development. These micronutrients help in the regulation of enzymatic and biochemical processes in plants. Nano micronutrient fertilizers contain these micronutrients in easily available forms. This helps in the efficient uptake of these micronutrients by plants. This type of fertilizer also helps in the improvement of plant development.

4.5 Nano-Coated Fertilizers

Nano-coated fertilizers contain traditional fertilizers. These fertilizers contain nano materials in the form of a coating. This coating helps in the regulation of the release of plant nutrients. This coating also helps in the improvement of the efficiency of plant

ISSN: 3049-2289

nutrients. This coating also helps in the reduction in the rate of application of plant nutrients. This type of fertilizer is helpful in precision agriculture.

5. Mechanism of Action

Nano fertilizers have an efficient mechanism of action, which makes them more effective compared to other fertilizers. The nanometer scale of these products allows them to have better interactions with plant systems compared to conventional products.

Entry into Plants:

There are different ways through which nano fertilizers enter plant systems. When these products are used as foliar sprays, the particles enter the plant through stomatal and cuticular surfaces of leaves. In the soil application method, the products enter plant systems through the root system of plants, passing through the apoplast and symplast.

Controlled Release:

Nano fertilizers have the ability to provide a continuous supply of plant nutrients through a slow release of these products. This process ensures that the products are released at a continuous rate, matching the growth of the plant, thus reducing the loss of nutrients through leaching and volatilization.

Targeted Transport:

Once inside the plant, the nanoparticles ensure the efficient transport of nutrients to the areas of need. This ensures that the plant has the nutrients it needs, which will improve its efficiency.

Enhanced Bioavailability:

Due to their reactivity, nano-fertilizers have the ability to enhance the bioavailability of nutrients, which will improve the uptake of the nutrients by the plant.

6. Advantages of Nano Fertilizers

Nano fertilizers have various advantages, both agronomical, economic, and environmental. These fertilizers are considered to be an alternative to existing fertilizers in modern agricultural practices.

6.1 Increased Crop Productivity

Nano fertilizers play an important role in increasing the productivity of crops. These fertilizers are highly beneficial to crops as they provide nutrients to the crops efficiently. This leads to an increase in the growth of crops. As a result, crops are healthy, and there is an increase in their yield as well as quality.

- Better plant growth
- Increased yield and quality

6.2 Higher Nutrient Use Efficiency

One of the advantages of nano fertilizers is that they have a high nutrient use efficiency. This efficiency of nano fertilizers can go up to 80-90%. This means that a greater percentage of nutrients will be used by the crops. This results in a lower requirement of fertilizers.

- Efficiency up to 80-90%
- Less fertilizer requirement

6.3 Cost Reduction

Although nano fertilizers may have a higher initial cost, they reduce overall input expenses in the long run. Lower application rates, reduced frequency of use, and minimized losses contribute to cost savings. Additionally, transportation and storage costs are lower due to smaller quantities required.

- Lower input costs in the long term
- Reduced transportation and storage

6.4 Environmental Protection

Nano fertilizers are environmentally friendly because they conserve nutrients from being lost through leaching, volatilization, and runoff. This helps in protecting the environment from degradation.

- Reduced nutrient losses
- Reduced soil and water pollution

ISSN: 3049-2289

6.5 Stress Tolerance

Nano fertilizers provide plants with resistance to abiotic stresses such as drought, salinity, and extreme temperatures.

- Enhances resistance to drought and other stresses

7. Applications of Nano Fertilizers

Nano fertilizers can be applied using different techniques depending on the requirements of the crops. The diversity of nano fertilizers enables their application in conventional as well as precision agriculture.

7.1 Foliar Application

The most effective method of using nano fertilizers is the foliar method of application. In this method, nano fertilizers are sprayed onto the leaves of plants. The nanoparticles are absorbed through the leaves because they are small enough to penetrate through the stomata of leaves.

- Most effective method
- Quick absorption of nutrients

7.2 Soil Application

In the soil application method of using nano fertilizers, the fertilizers are applied to the soil. The fertilizers are absorbed through the roots of plants. Nano fertilizers are beneficial for plants because they are small enough to move freely in the soil.

- Nutrients absorbed through roots

7.3 Seed Treatment

Nano fertilizers can also be applied to the seeds to promote germination and seedling development. They help to promote seed vigor, root development, and tolerance to environmental stress in the initial crop development.

- Improves germination and early growth

7.4 Fertigation and Drip Systems

Nano fertilizers can also be applied through fertigation and drip irrigation. This is one of the best modes of application because it ensures precision in the application of the fertilizers.

- Precise nutrient delivery

8. Status of Nano Fertilizers in India

India has emerged as a global leader in the development and application of nano fertilizers as part of its initiatives to encourage sustainable agriculture. With the growing scarcity of resources and need to increase crop production, nano fertilizers have attracted considerable attention among researchers, policymakers, and farmers. A major achievement in this area has been the development of Nano Urea (Liquid) that has been popularized as an alternative to regular urea. It is easy to use, needs less quantity, and has higher nutrient efficiency.

The Government of India has been supporting the promotion of nano fertilizers through various initiatives, awareness programs, and policies. Various agricultural institutions have been conducting training programs to educate farmers on the benefits of using nano fertilizers. Demonstrations have shown encouraging results in enhancing crop production and using fewer fertilizers. Although the adoption rate is still in the early stages, it is gradually increasing as more farmers become aware of its advantages. The integration of nano fertilizers with modern practices such as precision farming and digital agriculture is expected to further boost their use in the coming years.

9. Limitations of Nano Fertilizers

Though nano fertilizers have many advantages, there are also certain limitations. The first limitation of nano fertilizers is their high production cost, which makes them expensive. This will not favor small farmers, as they will not afford them. Another limitation of nano fertilizers is the lack of technical knowledge regarding their application, which might result in their inefficient use. There is also a lack of information regarding their long-term effects, which needs further research. Finally, there are no proper guidelines regarding their usage, which might result in toxicity, thereby affecting plant growth.

10. Environmental Impact

Nano fertilizers have a substantial impact on the agricultural environment, which is either beneficial or detrimental depending on their application.

Positive Environmental Impact

Nano fertilizers contribute to environmental sustainability by maximizing the utilization and minimizing the loss of nutrients. The controlled release mechanism prevents leaching, which in turn prevents the contamination of underground water. This ensures the maintenance of ecological balance in the environment. Moreover, nano fertilizers contribute to the improvement of soil health by maintaining optimal nutrient levels in the soil. The next positive impact is the reduction in greenhouse gases, mainly those containing nitrogen, due to optimal utilization.

- ❖ Prevention of nutrient leaching
- ❖ Improvement in soil health
- ❖ Reduction in greenhouse gases

Potential Risks

Though there are many advantages of using nano fertilizers, there are certain risks involved with the continuous use of these fertilizers. The continuous use of nano fertilizers might result in the accumulation of nanoparticles in the soil. This might, in turn, affect the soil properties. In addition, there might also be a chance of affecting the microorganisms present in the soil, which are important for soil fertility.

- ❖ Accumulation of nanoparticles in soil
- ❖ Possibility of affecting soil microorganisms

11. Future Prospects

Nano fertilizers have immense potential to change the face of modern agriculture and contribute to the development of sustainable agriculture. Current research is geared toward the development of smart nano fertilizers that can sense the needs of plants and respond to environmental changes to release nutrients in a highly accurate and efficient way. The application of nano fertilizers with modern technologies such as artificial intelligence (AI), remote sensing, and precision farming will result in more efficient use of nutrients for increased productivity at a reduced cost to the environment. Another area of research is the development of customized nano fertilizers to meet the needs of different crops, soil types, and climatic conditions. In the future, nano fertilizers will play a significant role in the development of sustainable agriculture through efficient use of resources, increased crop resilience to climatic changes, and meeting the demands of food security.

- ❖ Development of smart nano fertilizers
- ❖ Integration of nano fertilizers with AI technology
- ❖ Customized nutrient formulations
- ❖ Key role in sustainable agriculture

12. Conclusion

Nano fertilizers are being considered a revolutionary technology that may change the face of modern agriculture through their potential to enhance nutrient utilization efficiency, crop productivity, and mitigate environmental pollution. Their potential to deliver nutrients in a controlled manner is seen as a viable alternative to conventional fertilizers. However, for their widespread application in modern agriculture, it is important to strengthen research on their long-term impacts, training of farmers, and development of regulatory frameworks. With their judicious application, nano fertilizers may play a significant role in the development of sustainable agriculture in the future.

References

Al Tawaha, A. R. M., Singh, A., Rajput, V. D., Varshney, A., Agrawal, S., Ghazaryan, K., ... & Shawaqfeh, S. (2024). Green nanofertilizers–the need for Modern Agriculture, Intelligent, and environmentally-friendly approaches. *Ecological Engineering & Environmental Technology*, *25*.

Aljanabi, H. A. Y. (2021). Effects of nano fertilizers technology on agriculture production. *Annals of the Romanian Society for Cell Biology*, *25*(4), 6728-6739.

Nongbet, A., Mishra, A. K., Mohanta, Y. K., Mahanta, S., Ray, M. K., Khan, M., ... & Chakrabartty, I. (2022). Nanofertilizers: a smart and sustainable attribute to modern agriculture. *Plants*, *11*(19), 2587.

Seleiman, M. F., Almutairi, K. F., Alotaibi, M., Shami, A., Alhammad, B. A., & Battaglia, M. L. (2020). Nano-fertilization as an emerging fertilization technique: why can modern agriculture benefit from its use?. *Plants*, *10*(1), 2.

Thirugnanasambandan, T. (2021). Advances of engineered nanofertilizers for modern agriculture. In *Plant-microbes-engineered nano-particles (PM-ENPs) nexus in agro-ecosystems: understanding the interaction of plant, microbes and engineered nano-particles (ENPS)* (pp. 131-152). Cham: Springer International Publishing.

Breeding for Nitrogen Use Efficiency: Wheat

Shrishti Srivastava[1], Dr. Piyusha Singh[2]* Stuti Singh[3]
[1]PhD Research Scholar, Department of Genetics and Plant Breeding, Acharya Narendra Deva University of Agriculture & Technology, Kumarganj, Ayodhya, 224 229 (U.P.)
[2]Assistant Professor, Department of Genetics and Plant Breeding Acharya Narendra Deva University of Agriculture & Technology, Kumarganj, Ayodhya, 224 229 (U.P.)
[3]PhD Research Scholar, Department of Agronomy, Acharya Narendra Deva University of Agriculture & Technology, Kumarganj, Ayodhya, 224 229 (U.P.)

Wheat is a cereal crop also referred as king of cereals. Nitrogen being the major macronutrient also play role in growth and development of crops. Nitrogen Use Efficiency is important for proper metabolism. Therefore, to prevent excessive use of nitrogen as it is harmful for sustainability of environment many breeding methods have been developed such as traditional breeding, gene-editing, molecular breeding, marker assisted selection and genome selection.

1.Introduction

Wheat belongs to the family Poaceae and is an annual crop also known as the king of cereal crops. Wheat can be diploid (2n = 2x = 14), tetraploid (2n = 4x = 28), or hexaploid (2n = 6x = 42). *Triticum aestivum* L., a hexaploid wheat (AABBDD), is often referred to as bread wheat. Wheat is evolved from wild grass with a center of origin in the Fertile Crescent. Nitrogen is an essential primary nutrient and macronutrient in plants, important for its growth and development, as it is a major constituent of amino acids, proteins, and chlorophyll. Nitrogen improves root system development (Fageria and Barbosa, 2001). It is a major component of compounds responsible for energy transfer, such as adenosine diphosphate (ADP) and adenosine triphosphate (ATP). Moll *et al.*,1982 defined Nitrogen Use Efficiency (NUE) as the weight of the grains divided by the amount of N available in the soil. Plants uptake nitrogen in the form of nitrate and ammonium. Application of nitrogen is important for crop growth. Wrong methods of application can lead to nitrogen loss via denitrification, volatilization, and leaching, which in turn pollute soil and water. Wheat being one of the most important cereal crops, also has a high uptake of nitrogen; as a result, it is an alarming point for climate mitigation and sustainable agriculture. Many breeding methods had been used for enhancing NUE in wheat, like traditional breeding method, CRISPR-Cas9, marker-assisted selection, etc.

2 Nitrogen Use Efficiency (NUE)

Nitrogen Use Efficiency is defined as the ability of plant to uptake nitrogen from soil or fertilizer and to produce grain or effective yield. It has three components namely, Nitrogen Uptake Efficiency (NUpE), Nitrogen Utilization Efficiency (NUtE) and Nitrogen Harvest Index.

NUE = NUpE x NUtE

2.1 Nitrogen Uptake Efficiency (NUpE)

Nitrogen taken up by plant with respect to per unit of nitrogen available in the soil, also called nitrogen uptake efficiency (NUpE)

2.2 Nitrogen Utilization Efficiency (NUtE)

Biomass production per unit nitrogen taken up from the soil through absorption, acquisition and utilized through assimilation and remobilization (Moll *et al.*,1982), also called nitrogen utilization efficiency (NUtE).

2.3 Nitrogen Harvest Index

The ratio of harvested N to total crop Nitrogen, defined as the nitrogen harvest index (NHI)

ISSN: 3049-2289

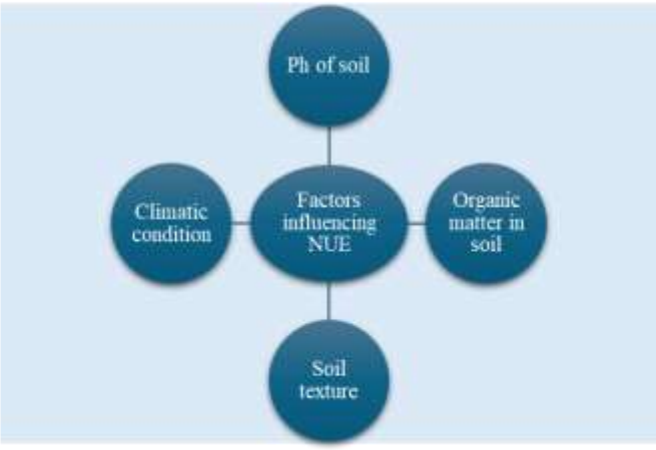


Figure 1. Factors influencing nitrogen use efficiency

3 Key Traits Influencing NUE of Wheat

3.1 Root size and density

Genetic variability among wheat varieties is widely present but it is also influence by soil nutrient availability. In nitrogen deficient condition there is increase in root biomass to the plant biomass. Root hairs have ability to absorb more nitrogen and reduce nitrate loss in environment via leaching (Brundrett *et al*., 2018 and Gastal *et al*.,2002).

3.2 Leaf Senescence at grain filling stage

Wheat plant requirement for nitrogen increases at grain filling stage. Hence, selection of plant with delayed leaf senescence will be beneficial as it is resultant of nitrogen accumulation or high uptake of nitrogen by plant.

3.3 Leaf and canopy photosynthesis per unit Nitrogen

Nitrogen in plants is mainly involved in photosynthesis by being present in mesophyll cells. Sunlight absorbed per unit nitrogen uptake, strategically distributing N vertically to align with light intensity gradients in the canopy and photosynthesis taken place on per unit of nitrogen per leaf.

3.4 Protein concentrations in grain

Wheat grains have starchy endosperm which consist of gluten protein. Gluten protein present is mixture of monomeric gliadins and polymeric glutenins. These group of protein constitutes of about 60 to 70% of the total nitrogen in the endosperm tissue. Whereas, there is inverse relation between grain protein content and yield. Hence, it is difficult to maintain quality and quantity of wheat at the same time (Cormier *et al*., 2016).

4 Breeding Approaches for enhancing NUE

4.1 Traditional breeding method

Conventional breeding programs have focused on selecting crop varieties with higher NUE. This method utilizes the natural genetic diversity present within crops to identify traits linked to efficient nitrogen uptake and utilization. By selecting and crossbreeding high-performing lines, researchers have been able to develop varieties that exhibit traits such as enhanced root architecture, increased nitrogen assimilation, and optimized nitrogen partitioning within the plant. In case of heterosis breeding, heterosis can be induced by chemical agent, male sterility or by crossing of two superior parents. Some of the studies showed that heterotic progeny has high yield and protein content as compare to pureline (Perezin *et al*.,1998). This indicates that hybrids may have better nitrogen uptake and higher NUE as compared to pure lines

4.2 Genetic engineering

For enhancing NUE genetic engineering and synthetic biotechnology is a beneficial breeding method. Legume crops have a symbiotic association with nitrogen-fixing bacteria. The main problem is for cereal crops with respect to nitrogen uptake. The nitrogenase-encoding gene, the nif gene, is introduced from species like *Klebsiella* and *Azotobacter* into E. coli has demonstrated varying degrees of nitrogenase activity (Bennett *et al*., 2023). Engineering bacteria that associate with cereal crops (e.g., *Pseudomonas protegens*) is promising but challenging, especially in establishing stable symbiosis. This method has been used to alter the genes responsible for nitrate transport i.e., NRT1.1, in crops such as rice, which leads to improvement in nitrogen uptake and growth of crop. Hence, the target modification of gene (regulatory gene) which is responsible for nitrogen signaling pathways has the ability to enhance overall NUE.

4.3 CRISPR-Cas9: Gene editing

CRISPR-Cas9 is a genome editing tool which can knock off the genes which have negative impact on nitrogen use efficiency. To achieve high NUE there can be two approaches via CRISPR-Cas9. Repression of negative regulators – Genes that limit nutrient uptake and utilization are silenced using tools like CRISPRi (CRISPR interference), dCas9-repressors, CRISPR-SunTag, and CRISPR/Cas9 mutagenesis. This removes inhibitory effects and enhances nutrient assimilation. The other one is activation of positive regulators – Beneficial genes involved in nutrient uptake, transport, and assimilation are upregulated using CRISPR activation systems and promoter engineering. This increases the plant's ability to absorb and efficiently use nutrients.

4.4 Molecular breeding

Molecular breeding method involves information at molecular level which includes protein, DNA, genes, and enzymes. Moreover, it has been believed that NR, NiR, GS, and GOGAT enzymes were major checkpoints controlling the N assimilatory pathway; for example, NR (Nitrate Reductase) enzyme activity improves NO_2 assimilation in Arabidopsis (Takahashi *et al*., 2001). Wheat genotypes with high NR show better N utilization under ample N (Vouillot *et al*., 1996, Anjana *et al*., 2011). Tobacco NR gene in wheat increases seed protein without the use of excessive fertilizer. Hence, we can say that NR is a promising breeding target for wheat NUE, yield and grain quality.

4.5 Marker-Assisted Selection (MAS) and Genomic Selection (GS)

Modern breeding methods that use genetic markers linked to high NUE attributes include marker-assisted selection and genomic selection. While GS uses genome-wide marker data to predict and identify plants with the greatest potential for NUE improvement, MAS selects plants with desirable genetic markers associated with efficient nitrogen utilization. Gene mapping and linking markers to candidate genes facilitates genome-aided breeding for nitrogen use efficiency(Yu and Buckler, 2006). Linkage analysis has been used majorly to focus on the agronomically important traits in plants, such as grain yield under various environmental conditions. However, QTL cloning is a successful but time taking procedure.

Genome-wide association studies (GWAS) help in identifying specific genetic regions or markers linked to important traits by using a diverse set of breeding lines. Whereas, genomic selection, selects superior individuals by the combined effects of many genes controlling a single trait of interest. Combining both GWAS and GS with marker-assisted selection can highly improve breeding efficiency by decreasing time, labour and specificity of gene selected for the trait of interest (NUE).

5. Conclusion

Wheat is an annual grass crop in which nitrogen is major component for metabolic activity. As far as for concern of environment sustainability and precise agriculture the main focus is on low input and high output without harming environment. Therefore, many key traits have been discovered which influences nitrogen uptake of plant like canopy, root density, leaf area and protein in grain. To produce varieties which high NUR identifying traits was necessary. Moreover, many breeding strategies were followed like selection over generation to identify the high NUE varieties but use of such breeding methods take a lot of time so advancement in breeding method was made by time and it leads to development of methods such as gene knock out: CRISPR-Cas9, molecular breeding, MAS and genome selection

References

1. Ali, A., Jabeen, N., Farruhbek, R., Chachar, Z., Laghari, A. A., Chachar, S., ... & Yang, Z. (2025). Enhancing nitrogen use efficiency in agriculture by integrating agronomic practices and genetic advances. *Frontiers in Plant Science*, *16*, 1543714.

ISSN: 3049-2289

2. Ali, Muhammad Arif & Danish, Subhan & Chaudhry, Usman & Hussain, Sajjad & Hassan, Waseem & Ahmad, Fiaz & Ali, Nawab. (2020). Role of Macronutrients in Cotton Production. 10.1007/978-981-15-1472-2_6

3. Anjana, Umar, S., Abrol, Y. P., & Iqbal, M. (2011). Modulation of nitrogen-utilization efficiency in wheat genotypes differing in nitrate reductase activity. *Journal of plant nutrition*, *34*(6), 920-933.

4. Bennett, E. M., Murray, J. W., & Isalan, M. (2023). Engineering nitrogenases for synthetic nitrogen fixation: From pathway engineering to directed evolution. *BioDesign Research*, *5*, 0005.

5. Brundrett, M. C., Ferguson, B. J., Gressshoff, P. M., Mathesius, U., Munns, R., Rasmussen, A., ... & Watt, M. (2018). Nutrient uptake from soils. *Plants in action. Australian Society of Plant Scientists, New Zealand Society of Plant Biologists, and New Zealand Institute of Agricultural and Horticultural Science, Australia*.

6. Cormier, F., Foulkes, J., Hirel, B., Gouache, D., Moënne-Loccoz, Y., & Le Gouis, J. (2016). Breeding for increased nitrogen-use efficiency: a review for wheat (T. aestivum L.). *Plant Breeding*, *135*(3), 255-278.

7. DoVale, J. C., DeLima, R. O., & Fritsche-Neto, R. (2012). Breeding for nitrogen use efficiency. In *Plant breeding for abiotic stress tolerance* (pp. 53-65). Berlin, Heidelberg: Springer Berlin Heidelberg.

8. Fageria, N. K., & Barbosa Filho, M. P. (2001). Nitrogen use efficiency in lowland rice genotypes. *Communications in Soil Science and Plant Analysis*, *32*(13-14), 2079-2089.

9. Fiaz, S., Wang, X., Khan, S. A., Ahmar, S., Noor, M. A., Riaz, A., ... & Alharthi, B. (2021). Novel plant breeding techniques to advance nitrogen use efficiency in rice: A review. *GM Crops & Food*, *12*(2), 627-646.

10. Foulkes, M. J., Hawkesford, M. J., Barraclough, P. B., Holdsworth, M. J., Kerr, S., Kightley, S., & Shewry, P. R. (2009). Identifying traits to improve the nitrogen economy of wheat: Recent advances and future prospects. *Field Crops Research*, *114*(3), 329-342.

11. Gastal, F., & Lemaire, G. (2002). N uptake and distribution in crops: an agronomical and ecophysiological perspective. *Journal of experimental botany*, *53*(370), 789-799.

12. Lammerts van Bueren, E. T., & Struik, P. C. (2017). Diverse concepts of breeding for nitrogen use efficiency. A review: Diverse concepts of breeding for nitrogen use efficiency. A review. *Agronomy for Sustainable Development*, *37*(5), 50.

13. Mălinaş, A., Vidican, R., Rotar, I., Mălinaş, C., Moldovan, C. M., & Proorocu, M. (2022). Current status and future prospective for nitrogen use efficiency in wheat (Triticum aestivum L.). *Plants*, *11*(2), 217.

14. Moll, R. H., Kamprath, E. J., & Jackson, W. A. (1982). Analysis and interpretation of factors which contribute to efficiency of nitrogen utilization 1. *Agronomy journal*, *74*(3), 562-564.

15. Neeraja, C. N., Voleti, S. R., Subrahmanyam, D., Surekha, K., & Rao, P. R. (2019). Breeding rice for nitrogen use efficiency. *Indian Journal of Genetics and Plant Breeding*, *79*(Sup-01), 208-215.

16. Oyewole, C. (2016). The wheat crop. *Kogi State University*.

17. Perezin, M., Corbellini, M., Accerbi, M., Vaccino, P., & Borghi, B. (1998). Bread wheat: F1 hybrid performance and parental diversity estimates using molecular markers. *Euphytica, 100*, 273–279.

18. Takahashi, M., Sasaki, Y., Ida, S., & Morikawa, H. (2001). Nitrite reductase gene enrichment improves assimilation of NO2 in Arabidopsis. *Plant physiology*, *126*(2), 731-741.

19. Vouillot, M. O., Machet, J. M., & Meynard, J. M. (1996). Relationship between the amount of reduced nitrogen accumulated in winter wheat shoots and the activity of nitrate reductase measured in situ. *European Journal of Agronomy*, *5*(3-4), 227-236.

20. Yu, J., & Buckler, E. S. (2006). Genetic association mapping and genome organization of maize. *Current opinion in biotechnology*, *17*(2), 155-160.

21. Zhao, X. Q., Nie, X. L., & Xiao, X. G. (2013). Over-expression of a tobacco nitrate reductase gene in wheat (Triticum aestivum L.) increases seed protein content and weight without augmenting nitrogen supplying. *PloS one*, *8*(9), e74678.

ISSN: 3049-2289

Clean Milk Production Techniques

Dr. Sanket Pathak[1]*, Dr. Rajdeep Madavi[2], Sampat Kumar Choudhary[3], Dr. Nongthombam Muhindro Singh[4]

[1]Ph.D. Scholar, Department of Livestock Production and Management, Maharashtra Animal and Fishery Sciences University, Nagpur-440006

[2]Department of Veterinary and Animal Husbandry Extension Education, Nagpur Veterinary College, Maharashtra Animal and Fishery Sciences University, Nagpur -440006

[3]SRF, ARYA Project, KVK – Gudamalani, Agriculture University, Jodhpur-344031

[4]Subject Matter Specialist (Vety.Sc.), Krishi Vigyan Kendra, Senapati, Hengbung, P.O. Kangpokpi-795002, Manipur.

Production of clean milk is important for the safety, quality, and shelf life of the milk. Clean milk production includes the maintenance of high levels of hygiene at each step, i.e., from animal health to transportation. Sanitation practices are important for the quality of milk, as they help in the reduction of microorganisms, which otherwise causes diseases, thereby improving the quality of the milk. Clean milk production increases the value of the product, which not only increases the income of farmers but also reduces the losses of the product. Despite its importance, there are certain difficulties that hinder its production, including a lack of awareness, infrastructure, and traditional practices.

1.Introduction

Milk is a very nutritious food that is rich in protein, fats, vitamins, and minerals. It is a very essential component of human diet. Milk is a very perishable food product that provides an ideal medium for the growth of various microorganisms. Milk can easily be contaminated if proper hygienic measures are not adopted at various stages, i.e., milking, handling, storage, and transportation. Such a situation not only affects the quality and storage life of milk but also increases health hazards to consumers.

The production of clean milk is very essential to maintain the quality, safety, and storage life of milk. It involves maintaining strict hygienic conditions at all stages, i.e., animal health, housing, milking, handling, storage, and transportation. This will help to minimize the chances of contamination to a greater extent. In countries like India, where dairy farming is a major occupation, improvement in milk quality is very essential to boost farmers' income. Therefore, clean milk production plays a major role in strengthening the dairy industry.

2. Definition of Clean Milk

Clean milk is described as "milk produced from healthy animals and subjected to strict conditions of production, handling, and storage, so that it is free from dirt, microorganisms, and chemical contaminants." Clean milk is therefore free from any visible dirt, microorganisms, and chemical contaminants, which makes it safe and suitable for consumption by humans.

Clean milk production focuses on reducing contamination in the milk from the time it is produced to the time it is transported to the consumer. Clean milk production ensures that the microbial count is low and free from any adulterants like antibiotics and pesticides, which may affect the quality and health of consumers.

Clean milk may be described in simple terms as "safe, hygienic, and quality milk free from impurities and suitable for consumption by humans."

ISSN: 3049-2289

Source: https://epashupalan.com/

3. Importance of Clean Milk Production

Clean milk production is significant in ensuring the safety, quality, and economic value of milk both to consumers and dairy farmers. Milk is highly perishable and easily spoiled. Therefore, maintaining hygiene in milk production and handling is essential in ensuring that the product does not easily deteriorate. Clean milk production is significant in ensuring that consumers receive a safe and quality product. This also ensures that dairy farming is profitable.

Clean milk production is essential in ensuring that consumers do not suffer from food-borne and zoonotic diseases. This also ensures that the milk consumed by human beings retains its nutritional value. Clean milk contains proteins, fats, vitamins, and minerals. This is significant in ensuring that dairy farmers receive a high price for their products. This also allows farmers to export their products to other countries.

- ❖ Ensures food safety and public health
- ❖ Increases shelf life of milk
- ❖ Improves nutritional quality
- ❖ Enhances market value and export potential
- ❖ Reduces spoilage and economic losses
- ❖ Prevents transmission of diseases

4. Sources of Milk Contamination

Milk can get contaminated by various sources. Milk is an ideal medium for microbial growth. Any minor negligence in maintaining hygiene can cause significant deterioration in the quality and safety of the milk. Understanding the sources of milk contamination is essential to implement proper clean milk production practices.

4.1 Animal Source

The health and hygiene of the animal also play a crucial role in determining the quality of the milk. Milk collected from diseased animals, especially mastitis and tuberculosis-affected animals, contains harmful microorganisms that can cause serious health hazards. Dirty udders and teats contaminated with dung, mud, and dust can also introduce microorganisms into the milk.

- ❖ Diseased animals (mastitis, tuberculosis)
- ❖ Dirty udder and teats

4.2 Environmental Source

The environment around the dairy farm is an important factor that influences milk hygiene. Dust, soil, dung, and flies in the animal shed are potential sources of contamination. Inadequate sanitation practices in the dairy farm can also contribute to contamination. In addition to this, contaminated water used for cleaning udders, utensils, or equipment can contaminate milk. Similarly, low-quality feed can also contribute to contamination.

- ❖ Dust, soil, dung, and flies
- ❖ Contaminated water and feed

4.3 Equipment Source

The milking equipment and utensils are important sources of contamination. Inadequate cleaning of milking equipment can leave milk deposits that provide an environment for microbial growth. If this equipment is reused without proper washing and sanitizing, it can contaminate fresh milk.

- ❖ Dirty milking utensils and machines

4.4Human Source

Human handling is another important source of contamination. Milkers who do not practice good

ISSN: 3049-2289

personal hygiene, have unwashed hands, unwashed clothes, or practice coughing and sneezing during milking can contaminate the milk. Therefore, good hygiene practices must be followed during milking.

- ❖ Poor hygiene of milkers

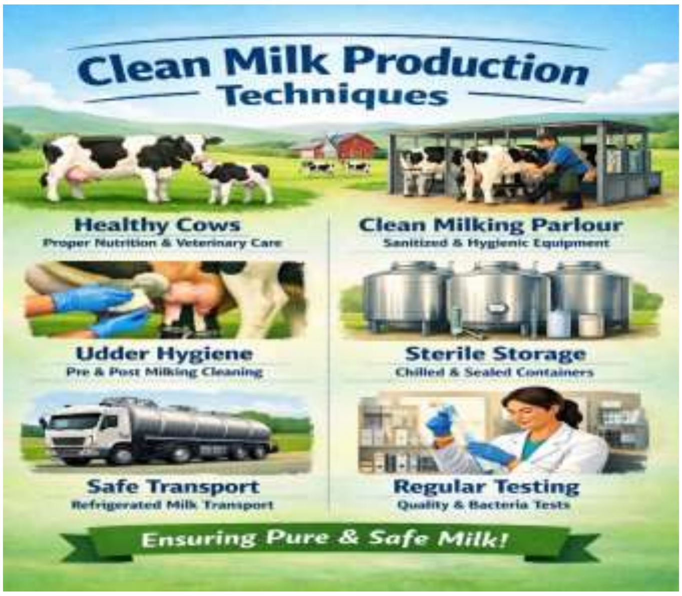
5. Clean Milk Production Techniques

Clean milk production techniques refer to the adoption of scientific and hygienic practices at all stages of milk production. These techniques help in minimizing contamination and producing good quality milk.

5.1Animal Health Management

Healthy animals form the basis of clean milk production. Regular monitoring of the health of animals, timely vaccination, and deworming of animals help in maintaining their health. Special emphasis has to be placed on the early detection and treatment of mastitis, as it has a direct impact on the quality of milk. Proper nutrition and drinking water supply help in maintaining the immunity power of the animals.

- ❖ Maintain disease-free animals
- ❖ Regular vaccination and deworming
- ❖ Early detection and treatment of mastitis
- ❖ Provide balanced nutrition and clean water



5.2 Clean Housing and Environment

A clean and hygienic environment reduces the risk of contamination. Animal sheds should be kept clean, dry, and well-ventilated. Proper drainage systems must be maintained to avoid water stagnation. Regular removal of dung and waste helps in maintaining sanitation, while effective control of flies and pests minimizes the spread of pathogens.

- ❖ Keep sheds clean and dry
- ❖ Proper drainage and ventilation
- ❖ Regular removal of dung and waste
- ❖ Control flies and pests

5.3 Hygienic Milking Practices

Before Milking

Preparation for milking is essential. Milkers are required to wash their hands thoroughly. The udder and teats are to be cleaned using clean water. A clean cloth is to be used to dry them. The milk that comes first is to be discarded.

- ❖ Wash hands thoroughly
- ❖ Clean udder and teats using clean water
- ❖ Dry udder and teats using clean cloth
- ❖ Discard first few streams of milk

During Milking

Hygienic conditions have to be maintained throughout the process. Milkers are required to use clean and sanitized utensils. Milking is not to be done by talking, coughing, or sneezing. The full-hand milking technique has to be followed to extract milk thoroughly without injuring the teats.

- ❖ Use clean and sanitized utensils
- ❖ Avoid talking, coughing, or sneezing
- ❖ Follow full-hand milking technique

After Milking

Hygienic conditions have to be maintained even after milking. The teats are to be dipped in an antiseptic solution to prevent diseases like mastitis. The milk has to be filtered immediately using a clean cloth to remove any impurities.

- ❖ Dip teats in antiseptic solution
- ❖ Filter milk using clean cloth

5.4 Clean Milking Equipment

The milking equipment should always be cleaned and sanitized. Stainless steel equipment is recommended because it can be easily cleaned and does not interact with milk.

- ❖ Stainless steel equipment recommended
- ❖ Equipment washed with hot water and detergent
- ❖ Equipment dried properly before use

5.5 Milk Handling and Storage

After milking, milk should be handled with care to ensure quality milk. Milk should be filtered and cooled quickly to a temperature below 4°C to slow bacterial growth. Milk should be stored in clean containers with covers to prevent contamination by dust, air, and other substances.

- ❖ Milk to be filtered quickly
- ❖ Milk to be cooled quickly to a temperature below 4°C
- ❖ Milk to be stored in clean containers with covers
- ❖ Milk to be protected from contamination by dust and air

5.6 Transportation of Milk

Milk transportation is important to ensure quality milk is delivered to the collection centers. Clean and closed containers should be used to carry milk. The milk should be delivered to collection centers as quickly as possible to ensure freshness.

- ❖ Clean and closed containers to be used to carry milk
- ❖ Milk to be delivered quickly to collection centers

6. Personal Hygiene of Milker

The personal hygiene of the milker is of critical importance in maintaining the quality of milk. Milk is more prone to microbial growth; hence, even a slight lapse in maintaining personal hygiene may result in the growth of harmful microorganisms in the milk. Therefore, personal hygiene is of critical importance in maintaining the quality of milk.

The personal hygiene of the milker requires that they wear clean and appropriate clothing when handling the animals and the milk. The hands of the milker should be washed properly with soap and clean water before and after milking to avoid the growth of harmful microorganisms in the milk. The fingernails of the milker should be short and clean because they may harbor more microorganisms. Furthermore, the milker should avoid coughing, sneezing, and spitting near the milking area.

It is also important to note that individuals suffering from infectious diseases, skin infections, and respiratory infections should not be involved in the milking process because they may contaminate the milk.

- ❖ Wear clean clothes
- ❖ Wash hands before milking
- ❖ Keep nails short and clean
- ❖ Avoid milking when sick

7. Quality Control Measures

Quality control measures are essential to ensure that milk is safe, hygienic, and suitable for consumption. These practices help in maintaining the standard quality of milk and preventing contamination throughout the production and supply chain. Regular monitoring and testing of milk enable early detection of any defects or impurities, ensuring consumer safety and better market acceptance.

Milk should be tested regularly to assess its overall quality, including physical, chemical, and microbiological parameters. Checking fat and Solid-Not-Fat (SNF) content is important to determine the nutritional value and detect any dilution or adulteration. Monitoring microbial load helps in evaluating the level of bacterial contamination and the hygienic conditions under which the milk is produced and handled.

Detection of adulteration is another critical aspect of quality control, as the addition of substances like water, starch, or chemicals can reduce milk quality and pose health risks. Therefore, implementing proper quality testing procedures at collection centers and processing units is necessary to ensure that only clean and safe milk reaches consumers.

- ❖ Regular testing of milk quality
- ❖ Checking fat and SNF content
- ❖ Monitoring microbial load
- ❖ Detection of adulteration

8. Common Milk-Borne Diseases

Milk can act as a medium for transmitting various infectious diseases if it is contaminated during production, handling, or storage. These diseases, known as milk-borne diseases, pose serious health risks to consumers and highlight the importance of maintaining strict hygiene in dairy practices.

Tuberculosis is caused by *Mycobacterium* species and can be transmitted through milk obtained from infected animals. Brucellosis, caused by *Brucella* bacteria, spreads through raw or unpasteurized milk and can lead to fever and joint pain in humans. Salmonellosis is another common disease caused by *Salmonella* bacteria, often resulting from poor hygiene and contaminated milk handling practices. Listeriosis, caused by *Listeria monocytogenes*, is particularly dangerous for pregnant women, newborns, and individuals with weakened immune systems. These diseases emphasize the need for proper sanitation, pasteurization, and clean milk production practices. By maintaining animal health, ensuring hygienic milking, and following safe storage and transportation methods, the risk of milk-borne infections can be significantly reduced.

- ❖ Tuberculosis
- ❖ Brucellosis
- ❖ Salmonellosis
- ❖ Listeriosis

Clean milk production plays a vital role in preventing these diseases and ensuring consumer safety.

9. Advantages of Clean Milk Production

Clean milk production offers numerous benefits for both consumers and dairy farmers by ensuring the safety, quality, and economic value of milk. Maintaining hygiene throughout production and handling significantly improves the overall standard of milk.

- ❖ **Safe and Hygienic Milk:** Clean milk is free from harmful microorganisms, dirt, and contaminants, making it safe for human consumption and reducing the risk of diseases.
- ❖ **Increased Shelf Life:** Hygienic production and proper handling reduce microbial load, which helps in extending the shelf life of milk and preventing early spoilage.
- ❖ **Higher Market Price:** High-quality clean milk fetches better prices in the market and is more acceptable for processing and export purposes.
- ❖ **Better Consumer Trust:** Consumers prefer clean and safe milk, which builds confidence and strengthens the reputation of dairy producers.
- ❖ **Reduced Spoilage Losses:** By minimizing contamination, clean milk production reduces wastage and economic losses, thereby increasing profitability for farmers.

10. Constraints in Clean Milk Production

Despite its importance, clean milk production faces several challenges that hinder its effective implementation, especially in developing countries. One of the major constraints is the lack of awareness among farmers regarding hygienic practices and the importance of milk quality. Many small and marginal farmers continue to follow traditional milking methods, which often do not meet scientific hygiene standards. Poor sanitation facilities in rural areas further contribute to contamination risks. Unclean animal sheds, improper waste disposal, and lack of drainage systems create an unhygienic environment for milk production. Additionally, limited access to clean and safe water makes it difficult to maintain cleanliness of animals, equipment, and milking areas. Another significant issue is inadequate training and extension services. Farmers often lack proper guidance on modern dairy management practices, including clean milk production techniques. As a result, they are unable to adopt improved methods effectively.

- ❖ Lack of awareness among farmers
- ❖ Traditional practices
- ❖ Poor sanitation facilities
- ❖ Limited access to clean water
- ❖ Inadequate training

11. Future Prospects

The future of clean milk production lies in the adoption of modern technologies and improved management practices. The use of automated and hygienic milking machines can significantly reduce human contact and contamination during milking. These machines ensure uniform and efficient milk extraction while maintaining hygiene standards.

Advancements in smart dairy farming, such as sensors and monitoring systems, can help track animal health, milk quality, and environmental conditions in real time. This enables timely interventions and better management decisions. Training and extension programs will play a vital role in educating farmers about clean milk practices and modern technologies. Government initiatives, subsidies, and policies aimed at promoting quality milk production will further encourage adoption.

- ❖ Adoption of modern milking machines
- ❖ Use of sensors and smart dairy systems
- ❖ Training and extension programs
- ❖ Government initiatives for quality milk production

12. Conclusion

Clean milk production is essential for ensuring high-quality dairy products and protecting public health. By adopting hygienic practices, maintaining animal health, and using clean equipment, contamination can be minimized. With increasing awareness and technological advancements, clean milk production can play a vital role in improving dairy productivity and farmers' income.

13.References

Bafanda, R. A., Nanda, R., Choudhary, F., Choudhary, M. S., & Shehjar, F. (2018). Clean milk production practices adopted by the dairy farmers of RS Pura in Jammu District. *Asian journal of agricultural extension, economics & sociology*, *26*(3), 1-10.

Kumawat, B. (2025). CLEAN MILK PRODUCTION AND MILKING METHODS. *Practical Manual Dairy Cattle and Buffaloes Production and Management*, 153.

Parkash, J., & Singh, G. CLEAN MILK PRODUCTION AND MILKING METHODS. *Practical Manual on Dairy Cattle and Buffaloes Production and Management*, 192.

Singh, V., & Gupta, J. (2015). Promoting clean milk production: The path for milk quality improvement. *Journal of Community Mobilization and Sustainable Development*, *10*(2), 163-167.

Wang, X., Demirci, A., Graves, R. E., & Puri, V. M. (2019). Conventional and emerging clean-in-place methods for the milking systems. In *Raw Milk* (pp. 91-115). Academic Press.

AGRICULTURE BULLETIN
ISSN: 3049-2289

Assessing the Combined Impacts of Climate Change, Nanoplastic Pollution, and Soil Degradation on Food Security

Lalit Krishna Yadav
Assistant Professor, Department of Soil Science and Agricultural Chemistry, Shri Vishwanath P.G. College, Kalan, Sultanpur, Uttar Pradesh, India

Introduction

Food security, defined by the consistent availability, access, utilization, and stability of sufficient, safe, and nutritious food, is essential for human health, economic growth, and social stability. As the global population grows, the pressure on agricultural systems and natural resources intensifies. This increasing demand faces serious challenges from interconnected environmental threats—particularly climate change, nanoplastic pollution, and soil degradation—that undermine food production and distribution.

Climate change disrupts weather patterns, water availability, and pest dynamics, creating uncertainty in crop yields. Nanoplastic pollution, a growing contaminant in soils and water, threatens soil health and food safety through its persistent and invasive nature. Meanwhile, soil degradation, driven by unsustainable land use and farming practices, reduces soil fertility and water retention, weakening crop resilience and increasing vulnerability to climate stress.

These factors interact in complex ways, amplifying their negative effects. For instance, extreme weather accelerates soil erosion, while nanoplastics disrupt key soil microbial communities. Degraded soils also release greenhouse gases, further intensifying climate change. Understanding these combined impacts is critical to developing integrated strategies that protect food systems and ensure sustainable food security amid environmental challenges.

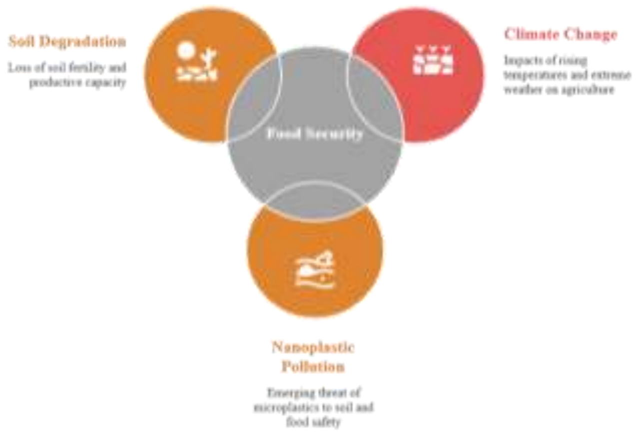


Figure 1: Foundations of Food Security

1. Climate Change and Food Security

Climate change exerts profound and multifaceted impacts on agriculture and food systems worldwide. The rise in global average temperatures, altered precipitation patterns, and increased frequency of extreme weather events disrupt the delicate balance required for crop and livestock production.

a) **Temperature Stress:** Elevated temperatures accelerate plant phenology, often shortening the growing period and reducing yields. Crops such as wheat and maize are particularly sensitive to heat stress during flowering and grain-filling stages. Heat also increases evapotranspiration rates, leading to water deficits and physiological stress.

b) **Altered Precipitation Patterns:** Shifts in rainfall timing and intensity create challenges in water availability. Drought conditions limit soil moisture, impeding seed germination and plant growth, while excessive rainfall can cause waterlogging and root damage.

ISSN: 3049-2289

c) **Extreme Weather Events:** The increasing occurrence of storms, floods, heatwaves, and frosts disrupt planting schedules, damage crops, and reduce harvests. These events also destroy infrastructure critical for food storage and distribution, compounding food insecurity.

d) **Pest and Disease Dynamics:** Warmer climates expand the geographical range of many pests and pathogens, increasing their reproduction rates and survival. This leads to heightened crop losses and necessitates increased use of pesticides, which have environmental and economic costs.

The cumulative effects of these climate-induced stresses reduce agricultural productivity, increase price volatility, and threaten the livelihoods of millions, particularly smallholder farmers in vulnerable regions.

2. Nanoplastic Pollution: An Emerging Threat

Nanoplastics, defined as plastic particles smaller than 100 nanometers, represent a relatively recent concern within environmental science. Their small size allows them to penetrate biological barriers and persist in the environment, raising questions about their impact on soil ecosystems and food safety.

a) **Sources and Pathways:** Nanoplastics enter agricultural systems through multiple routes including irrigation with contaminated water, application of biosolids or sewage sludge as fertilizer, atmospheric deposition, and breakdown of larger plastic debris in soils.

b) **Soil Microbial Disruption:** Soil microorganisms play a vital role in nutrient cycling, organic matter decomposition, and soil structure maintenance. Nanoplastics can adsorb onto microbial cells, interfere with enzyme activities, and alter microbial community composition, thereby impairing soil fertility.

c) **Plant Uptake and Translocation:** Emerging studies indicate that some plants can absorb nanoplastics through roots and translocate them to shoots and leaves. This uptake may interfere with nutrient absorption, photosynthesis, and overall plant health, potentially reducing yields.

d) **Toxicity and Bioaccumulation:** Nanoplastics may carry toxic additives or adsorbed pollutants such as heavy metals and persistent organic pollutants. Their accumulation in soil organisms and plants raises concerns about trophic transfer and human exposure through the food chain.

The long-term ecological and health consequences of nanoplastic contamination remain under investigation, but their potential to undermine soil health and food safety is increasingly recognized.

3. Soil Degradation and Its Role in Food Insecurity

Soil degradation is a widespread problem that diminishes the productive capacity of land and threatens sustainable agriculture. It arises from both natural processes and unsustainable human activities.

a) **Erosion:** Loss of topsoil through wind and water erosion removes nutrient-rich layers essential for plant growth. It also reduces soil organic carbon stocks, impairing soil structure and water retention.

b) **Nutrient Depletion:** Intensive farming without adequate nutrient replenishment leads to exhaustion of essential macro- and micronutrients, forcing reliance on synthetic fertilizers which can cause further environmental harm.

c) **Salinization:** In arid and semi-arid regions, improper irrigation practices cause salt accumulation in soils, creating hostile conditions for most crops and reducing arable land.

d) **Soil Compaction:** Heavy machinery use and overgrazing compact soils, reducing pore space, limiting root penetration, and impairing water infiltration and aeration.

The degradation of soils results in lower yields, increased vulnerability to climatic stresses, and higher input costs, all of which contribute to food insecurity, especially among resource-poor farmers.

ISSN: 3049-2289

Table 1: Combined Effects on Food Security

Interaction Type	Combined Effect	Impact on Agriculture	Food Security Outcome
Climate × Soil Degradation	Accelerated erosion & moisture loss	Reduced productivity	Increased vulnerability
Climate × Nanoplastics	Enhanced pollutant mobility	Crop contamination risks	Food safety concerns
Nanoplastics × Soil Degradation	Microbial dysfunction	Poor nutrient cycling	Lower yield and quality
All Three Combined	Ecosystem destabilization	Severe crop stress	High risk of food insecurity

4. Interactions Between Climate Change, Nanoplastics, and Soil Degradation

These three environmental stressors do not operate in isolation but interact in complex ways, often reinforcing each other's negative impacts.

a) **Climate Change Amplifying Soil Degradation:** Increased rainfall intensity from climate change accelerates soil erosion, while prolonged droughts exacerbate salinization and organic matter loss. Temperature changes also affect soil microbial activity, influencing nutrient cycling.

b) **Nanoplastics Exacerbating Soil Degradation:** Nanoplastic particles disrupt soil microbial communities vital for maintaining soil structure and fertility. This interference can accelerate degradation processes and reduce soil resilience to climatic stresses.

c) **Climate Change Influencing Nanoplastic Dynamics:** Changes in precipitation and temperature regimes affect the transport, distribution, and degradation rates of nanoplastics in soil and water systems, potentially increasing their bioavailability and toxicity.

d) **Feedback Loops:** Degraded soils sequester less carbon, contributing to increased atmospheric greenhouse gases and further climate change. This creates a vicious cycle where environmental degradation fuels climatic shifts, which in turn worsen soil conditions.

Understanding these interactions is crucial for designing holistic interventions that address multiple threats simultaneously.

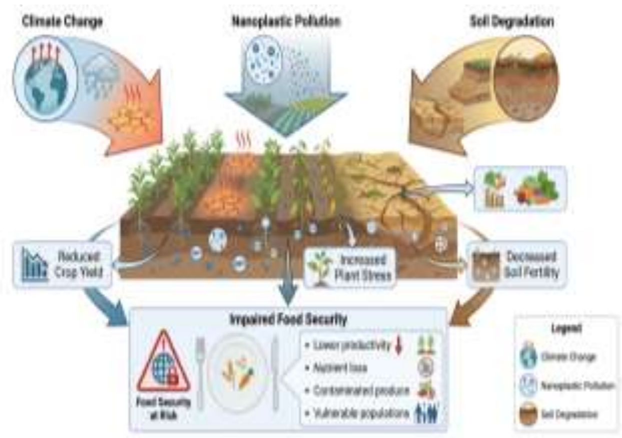


Figure 2: Combined Impacts of Climate Change, Nanoplastic Pollution, and Soil Degradation on Food Security

5. Implications for Food Security

The combined effects of climate change, nanoplastic pollution, and soil degradation jeopardize all four pillars of food security:

a) **Availability:** Declines in crop and livestock productivity reduce the overall food supply. Soil degradation and climate extremes lower yields, while nanoplastic contamination may reduce plant vigor.

b) **Access:** Economic losses due to decreased productivity and increased input costs limit farmers' purchasing power and access to food. Food price volatility caused by supply instability further restricts access, especially for vulnerable populations.

c) **Utilization:** The presence of nanoplastics and associated toxicants in food raises concerns about food safety and nutritional quality. Soil degradation can also reduce nutrient density in crops.

d) **Stability:** Increased variability in production due to climate variability and soil degradation leads to unstable food supplies and fluctuating prices, heightening the risk of food crises.

6. Regional Variability of Impacts

The severity and nature of these combined threats vary significantly across regions due to differences in climate, soil types, agricultural systems, and socioeconomic factors.

a) **Sub-Saharan Africa:** Characterized by dependence on rain-fed agriculture, widespread soil degradation, and limited adaptive capacity, this region faces acute food security risks exacerbated by climate variability and emerging pollution.

b) **South Asia:** Monsoon variability, expanding irrigation-induced salinity, and increasing plastic pollution from urbanization pose significant challenges to agricultural sustainability.

c) **Latin America:** Deforestation, land-use change, and soil erosion compound climate impacts, with emerging concerns about plastic contamination in agricultural soils.

d) **Developed Countries:** While technological advances provide some buffer, challenges remain in managing plastic pollution and adapting farming practices to changing climate conditions.

7. Socioeconomic and Health Consequences

The environmental challenges discussed extend beyond agriculture, impacting human health, livelihoods, and social stability.

a) **Livelihoods:** Small-scale farmers and pastoralists, often with limited resources, bear the brunt of productivity losses, increasing poverty and food insecurity.

b) **Nutrition:** Reduced crop diversity and soil nutrient depletion lower dietary quality, contributing to malnutrition and micronutrient deficiencies.

c) **Health Risks:** Consumption of food contaminated with nanoplastics and associated toxic substances poses potential health risks, including inflammation, endocrine disruption, and bioaccumulation effects.

d) **Migration and Conflict:** Food insecurity can drive rural-urban migration and exacerbate social tensions, potentially leading to conflicts over scarce resources.

Addressing these challenges requires integrated approaches that combine environmental management with social protection and public health initiatives.

8. Technological Innovations and Research Frontiers

Advances in science and technology offer promising avenues to better understand and mitigate these intertwined threats.

a) **Precision Agriculture:** Technologies such as remote sensing, drones, and AI enable real-time monitoring of crop health, soil conditions, and environmental stressors, facilitating targeted interventions that optimize resource use.

b) **Bioremediation:** Research into microbial and plant-based methods to degrade or immobilize nanoplastics and restore soil quality is advancing, offering sustainable remediation options.

c) **Nanoplastic Detection and Monitoring:** Development of sensitive analytical techniques is critical to quantify nanoplastic presence and understand their ecological and physiological impacts.

d) **Climate Modeling:** Enhanced climate models with finer spatial resolution improve predictions of localized impacts, informing adaptive agricultural practices.

Investment in interdisciplinary research is essential to translate these innovations into practical solutions.

9. Policy Frameworks and International Cooperation

Effective mitigation and adaptation require coherent policies and collaboration across sectors and borders.

a) **Integrated Environmental Policies:** Harmonizing climate action, pollution control, soil conservation, and agricultural development policies ensures synergistic outcomes.

b) **Plastic Waste Management:** Global agreements to reduce plastic production, improve recycling infrastructure, and prevent environmental leakage are vital to curb nanoplastic pollution.

c) **Soil Conservation Programs:** Incentivizing sustainable land management practices through subsidies, technical support, and education promotes soil restoration.

d) **Capacity Building:** Empowering farmers and communities with knowledge, access to technologies, and financial resources enhances resilience.

e) **Data Sharing and Monitoring:** Establishing global platforms for environmental and food security data supports informed decision-making and early warning systems.

Multilateral cooperation involving governments, NGOs, academia, and the private sector is key to addressing these global challenges.

10. Community Engagement and Indigenous Knowledge

Harnessing local knowledge and involving communities in environmental stewardship strengthens food security efforts.

a) **Traditional Practices:** Indigenous and local farming methods such as crop diversification, agroforestry, and water harvesting enhance resilience and sustainability.

b) **Participatory Approaches:** Engaging communities in planning and implementation ensures that interventions are culturally appropriate and socially accepted.

c) **Education and Awareness:** Raising awareness about environmental threats and sustainable practices empowers stakeholders to adopt adaptive behaviors.

Integrating scientific research with indigenous knowledge creates more robust and context-sensitive solutions.

11. Future Outlook and Urgency for Action

The convergence of climate change, nanoplastic pollution, and soil degradation presents a critical threat to global food security that demands urgent, coordinated action. Without intervention, these forces will continue to degrade agricultural productivity, compromise food safety, and exacerbate social inequities. However, through innovative science, inclusive policies, community engagement, and international cooperation, it is possible to build resilient food systems. These systems can sustain growing populations while preserving ecosystem health and promoting social well-being.

References

Kamble, M. T., Medhe, S. V., Chavan, B. R., Kettawan, A., Jeamsripong, S., & Pirarat, N. (2026). Climate Change Interacts with Plastic Stressors and Amplifies Food Insecurity. In *Plastic Tides: Tackling Plastic Pollution for Global Food Security* (pp. 303-345). Cham: Springer Nature Switzerland.

Chatterjee, A., & Ramavat, A. (2025). Impact of Environmental Pollution on Food Security. In *Municipal Waste Management: Policies and Strategies* (pp. 46-59). GB: CABI.

Zhang, D., Ng, E. L., Hu, W., Wang, H., Galaviz, P., Yang, H., ... & Liu, H. (2020). Plastic pollution in croplands threatens long-term food security. *Global Change Biology*, *26*(6), 3356-3367.

ISSN: 3049-2289

Sharma, A., Kumar, M., & Sharma, P. (2024). *Environmental Challenges in Attaining Food Security* (Vol. 9). Elsevier.

Abubakr, A., Amin, A., & Malik, M. M. (Eds.). (2025). *Microplastics: Ecological and Food Security Implications*. Springer.

ISSN: 3049-2289

Decision Support Systems for Smart and Efficient Crop Management

Nitesh, Paras Arya, Lokesh Bohra, Nishapal
Ph.D. Research Scholar, Department of Agronomy, Govind Ballabh Pant University of Agriculture and Technology, Pantnagar

Introduction

Decision Support Systems (DSS) in agriculture are sophisticated technological frameworks designed to assist farmers and agronomists in making informed, data-driven decisions. These systems synthesize a wide array of data, including environmental, biological, and economic information, to optimize crop management practices. The rising global population, climate variability, resource constraints, and environmental concerns necessitate a shift from traditional intuition-based farming to precision agriculture, where DSS plays a pivotal role. By enabling adaptive management through real-time data processing and predictive analytics, DSS enhances productivity, sustainability, and profitability in farming.

The evolution of DSS is closely tied to advances in computing, sensor technology, and data science. Modern DSS platforms integrate real-time data acquisition with machine learning and spatial analysis, providing actionable insights tailored to specific farm conditions. This scientific approach allows farmers to respond dynamically to changing environmental and market factors, improving resilience and efficiency.

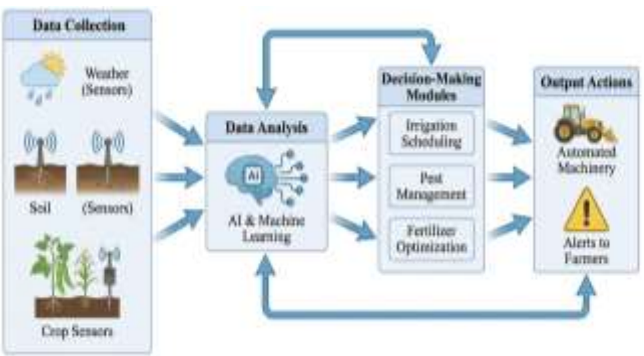


Figure 1: Decision Support Systems for Smart and Efficient Crop Management

Key Components of Crop Management Decision Support Systems

1. Data Collection and Integration

The foundation of effective DSS lies in comprehensive, accurate, and timely data collection from heterogeneous sources:

a) **Remote Sensing and Satellite Imagery:** These technologies provide large-scale, frequent monitoring of crop health indicators such as the Normalized Difference Vegetation Index (NDVI), soil moisture, and biomass. Multispectral and hyperspectral imaging enable early detection of nutrient deficiencies, pest infestations, and water stress, facilitating timely interventions.

b) **Internet of Things (IoT) Sensors:** Ground-based sensors deployed throughout the field measure soil moisture, temperature, pH, nutrient concentrations, and microclimate variables such as humidity and air temperature. Additionally, sensors on machinery monitor operational status and efficiency. Continuous data streams from IoT devices enable granular monitoring and immediate anomaly detection.

c) **Weather Forecasts:** Accurate, localized meteorological data are integrated to inform irrigation scheduling, pest control, and harvesting operations. DSS platforms utilize short- and long-term weather predictions to anticipate environmental stressors and optimize management practices.

d) **Historical Farm Data:** Archival records of past yields, crop rotations, pest and disease outbreaks, and management interventions provide critical baselines for trend analysis and model calibration, improving predictive accuracy.

ISSN: 3049-2289

e) **Market Data:** Real-time commodity prices, demand forecasts, and supply chain logistics are incorporated to align production decisions with market opportunities, enhancing economic outcomes.

Table 1: Components and Functionalities of Decision Support Systems in Agriculture

Component	Description	Technology Used	Function in Crop Management	Impact (%)
Data Acquisition	Collection of field and environmental data	IoT sensors, satellites, drones	Provides real-time field information	Improves accuracy (20–40%)
Database Management	Storage and processing of data	Cloud computing, big data systems	Organizes and retrieves data efficiently	Faster decision-making
Analytical Models	Predictive and simulation models	AI, machine learning	Forecast yield, pests, and weather risks	15–35% better predictions
User Interface	Interaction platform for users	Mobile apps (e.g., Kisan Suvidha)	Easy access to advisories	Higher adoption rates
Decision Engine	Generates recommendations	Algorithms, rule-based systems	Suggests optimal practices	20–30% efficiency gain
Communication System	Dissemination of information	SMS, apps, web portals	Timely delivery of advisories	Improved response time

2. Data Processing and Analytics

Data collected from diverse sources undergo cleaning, normalization, and integration to prepare for analysis. Advanced machine learning algorithms—such as regression models, classification trees, and clustering techniques—extract patterns and generate predictions. Geographic Information Systems (GIS) facilitate spatial analysis, visualizing field variability and enabling site-specific management. Scenario simulation models allow farmers to compare the outcomes of different management strategies, balancing yield optimization with cost efficiency and environmental sustainability.

3. User Interface and Visualization

DSS platforms prioritize user-friendly design to ensure accessibility and interpretability. Interactive dashboards present key performance indicators, alerts, and recommendations through charts, heat maps, and trend analyses. Mobile applications extend accessibility, allowing farmers to receive real-time updates and input data remotely. Customizable interfaces accommodate users with varying levels of technical expertise, from smallholder farmers to agricultural specialists.

4. Decision Modeling and Scenario Analysis

Decision models embedded within DSS evaluate multiple management scenarios, such as varying irrigation schedules or fertilizer application rates. These models incorporate agronomic, economic, and environmental parameters to simulate potential outcomes, enabling farmers to assess trade-offs and make strategic choices. Environmental impact assessments, including nutrient runoff and greenhouse gas emissions, can be integrated to support sustainable practices.

Applications of Decision Support Systems in Crop Management

1. Precision Irrigation Management

Water is a critical and often limited resource in agriculture. DSS optimizes irrigation by integrating soil moisture data, crop water requirements, and

ISSN: 3049-2289

weather forecasts. This precision irrigation approach ensures that crops receive adequate water without excess, conserving water resources and reducing energy costs. Automated irrigation systems linked to DSS adjust water delivery dynamically based on real-time sensor feedback, preventing under- or over-irrigation, which can lead to yield loss or soil degradation.

2. Nutrient Management

Efficient nutrient management is essential for maximizing crop productivity while minimizing environmental harm. DSS analyzes soil nutrient profiles and crop nutrient demands to recommend precise fertilizer types, quantities, and application timings. This targeted approach reduces nutrient leaching and runoff, protecting water quality and enhancing soil health. Some DSS incorporate nutrient use efficiency models, optimizing application methods such as foliar sprays or soil incorporation.

3. Pest and Disease Management

DSS integrates pest population monitoring, climatic data, and crop phenology models to forecast pest outbreaks and disease risks. Early warning systems enable farmers to implement targeted, timely interventions, reducing dependence on broad-spectrum pesticides. This supports integrated pest management (IPM) strategies, preserving beneficial organisms and minimizing chemical residues in the environment.

4. Crop Selection and Rotation Planning

By evaluating soil characteristics, climate data, and market trends, DSS advises on optimal crop selection and rotation sequences. Crop rotation is a critical practice for maintaining soil fertility, disrupting pest and disease cycles, and improving farm resilience. DSS models allow farmers to simulate different rotation scenarios, balancing short-term profitability with long-term sustainability.

5. Yield Prediction and Harvest Planning

Accurate yield forecasts assist farmers in optimizing labor allocation, machinery scheduling, storage management, and marketing strategies. DSS uses historical data, current crop status, and environmental variables to predict yields under various management scenarios. These predictions help coordinate supply chains and reduce post-harvest losses.

6. Resource Optimization and Cost Reduction

DSS identifies inefficiencies in farm operations by analyzing input usage, machinery performance, and labor deployment. Recommendations focus on reducing waste, optimizing machinery routes, and improving operational scheduling. These improvements contribute to lowering production costs and increasing profitability.

Table 2: Applications and Benefits of DSS in Smart Crop Management

Application Area	DSS Intervention	Mechanism	Impact on Productivity /Efficiency (%)	Outcome
Irrigation Management	Smart irrigation scheduling	Soil moisture and weather data integration	20–50% water saving	Improved water use efficiency
Nutrient Management	Site-specific nutrient recommendation	Soil test + crop model integration	15–30% yield increase	Reduced fertilizer use
Pest & Disease Management	Early warning systems	Predictive modeling and alerts	20–40% loss reduction	Timely intervention
Crop Planning	Crop selection and	Climate and marke	10–25% yield improvement	Risk minimization

ISSN: 3049-2289

	sowing decisions	t data analysis		
Yield Prediction	Forecasting tools	AI-based simulation models	15–35% accuracy improvement	Better planning
Precision Farming	Variable rate application	GPS and sensor-based systems	20–40% input efficiency	Cost reduction
Market Intelligence	Price forecasting	Data analytics and trends	10–30% income increase	Better price realization
Climate Risk Management	Weather-based advisories	Real-time forecasting systems	15–30% risk reduction	Climate resilience

Challenges in Implementing Decision Support Systems

1. Data Quality and Availability

The reliability of DSS outputs depends on the accuracy and completeness of input data. Sensor malfunctions, data gaps, or erroneous inputs can lead to suboptimal recommendations. Establishing robust data validation, calibration, and maintenance protocols is essential for system reliability.

2. Technology Access and Literacy

Smallholder farmers, especially in developing regions, often face barriers such as limited internet connectivity, lack of access to smartphones or computers, and low digital literacy. These challenges hinder DSS adoption and effective use. Tailored training programs, simplified interfaces, and offline functionalities can help bridge this gap.

3. Cost of Implementation

Initial investments in hardware (sensors, IoT devices), software licenses, and training can be prohibitive for many farmers. Subsidies, cooperative purchasing models, and scalable, modular DSS solutions can facilitate broader adoption.

4. Integration Complexity

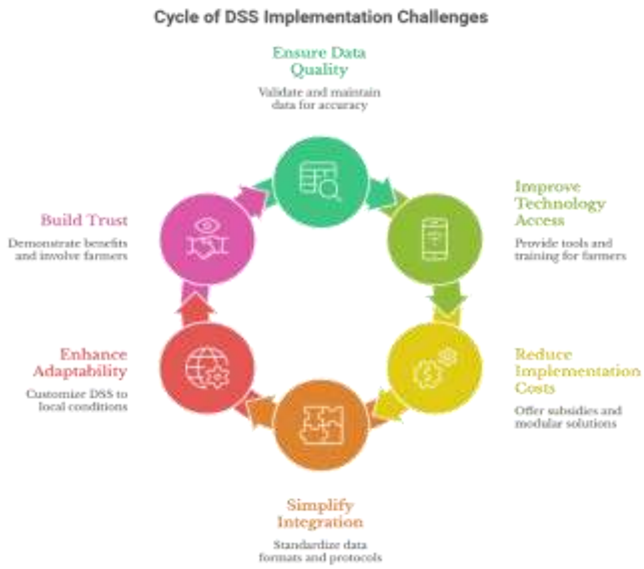
DSS must harmonize heterogeneous data sources and ensure interoperability among various technologies and platforms. Developing standardized data formats and communication protocols is critical for seamless integration.

5. Adaptability and Customization

Farming practices vary widely by region, crop type, and socio-economic context. DSS must be flexible and customizable to local conditions to provide relevant and actionable recommendations. Modular system designs and localized model calibration improve relevance and usability.

6. Trust and Adoption

Farmers may be reluctant to rely on automated recommendations without understanding the underlying logic or seeing tangible benefits. Building trust through transparency, participatory system development, user education, and demonstration projects is vital for sustained adoption.



Future Trends and Innovations

1. Artificial Intelligence and Machine Learning

AI and machine learning will enhance DSS capabilities by improving predictive accuracy and enabling autonomous, real-time decision-making. Deep learning models will process complex datasets, capturing nonlinear relationships and interactions within agroecosystems.

2. Big Data and Cloud Computing

Cloud-based platforms will facilitate the integration and processing of massive datasets from multiple farms, enabling regional-scale analytics and benchmarking. Big data approaches will uncover novel insights into crop-environment interactions and management efficacy.

3. Blockchain Technology

Blockchain will enable secure, transparent data sharing among stakeholders, enhancing traceability, certification, and trust within agricultural supply chains. This can improve data integrity and facilitate compliance with sustainability standards.

4. Mobile and Edge Computing

Edge computing devices will process data locally, reducing latency and dependence on continuous internet connectivity. Mobile DSS applications will expand accessibility to remote and resource-constrained farmers, supporting inclusive digital agriculture.

5. Integration with Robotics and Automation

Robotic platforms for seeding, spraying, and harvesting will be guided by DSS outputs, improving precision, reducing labor requirements, and enhancing operational efficiency.

6. Climate-Smart Agriculture

DSS will increasingly incorporate climate adaptation strategies, such as recommending drought-tolerant crop varieties, optimizing planting dates, and assessing carbon footprints. These features will support resilient, sustainable farming systems in the face of climate change.

Conclusion

Decision Support Systems are transforming agriculture by enabling smart, efficient, and sustainable crop management. By integrating diverse data sources and advanced analytics, DSS empowers farmers to optimize resource use, mitigate risks, and enhance economic returns while protecting environmental health. Overcoming challenges related to data quality, technology access, affordability, and system customization is crucial to unlocking the full potential of DSS globally. As agriculture confronts increasing pressures from population growth and climate change, these systems will serve as essential tools for ensuring food security and sustainable rural livelihoods.

References

Tamayo, R. A. C., Ibarra, M. L., & Macías, J. A. G. (2010, September). Better crop management with decision support systems based on wireless sensor networks. In *2010 7th International Conference on Electrical Engineering Computing Science and Automatic Control* (pp. 412-417). IEEE.

Gallardo, M., Elia, A., & Thompson, R. B. (2020). Decision support systems and models for aiding irrigation and nutrient management of vegetable crops. *Agricultural Water Management*, *240*, 106209.

Zhai, Z., Martínez, J. F., Beltran, V., & Martínez, N. L. (2020). Decision support systems for agriculture 4.0: Survey and challenges. *Computers and Electronics in Agriculture*, *170*, 105256.

Bhardwaj, S., & Sharma, R. Decision Support Systems and Artificial Intelligence in Crop Management. *Agronomy: Fundamentals, Systems and Technological Innovations*, 374.

Dabre, K. R., Lopes, H. R., & D'monte, S. S. (2018, January). Intelligent decision support system for smart agriculture. In *2018 International Conference on Smart City and Emerging Technology (ICSCET)* (pp. 1-6). IEEE.

AGRICULTURE BULLETIN
ISSN: 3049-2289

Contemporary Marketing Strategies and Supply Chain Integration in Agribusiness

Tanisha Negi
B.Sc. (hons.) Agriculture, Govind Ballabh Pant University of Agriculture and Technology, Pantnagar

Introduction

Agribusiness is a critical sector that bridges agriculture and commerce, playing a vital role in global food security, rural development, and economic growth. The dynamic nature of consumer preferences, technological advancements, and increasing environmental concerns have necessitated the adoption of contemporary marketing strategies and efficient supply chain integration within agribusiness. These developments aim to enhance competitiveness, sustainability, and profitability while addressing the challenges posed by globalization, market volatility, and resource constraints. This article explores the key contemporary marketing strategies and supply chain integration practices shaping agribusiness today, emphasizing their theoretical foundations, practical applications, and implications for future growth.

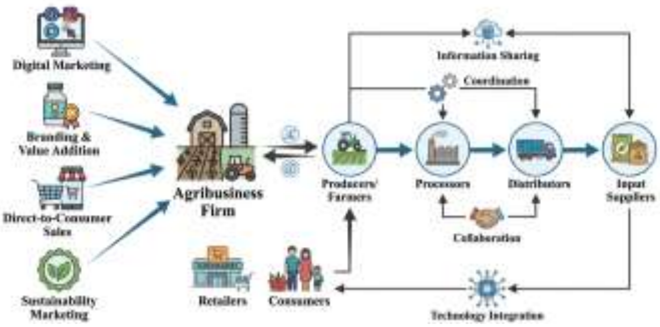


Figure 1: Contemporary Marketing Strategies and Supply Chain Integration in Agribusiness

1. Contemporary Marketing Strategies in Agribusiness

1.1 Digital Marketing and E-commerce

Digital transformation has revolutionized agribusiness marketing by providing new avenues for engagement, promotion, and sales. Digital marketing leverages social media platforms, websites, mobile applications, and email campaigns to reach diverse consumer segments directly. This approach allows agribusiness firms to bypass traditional intermediaries, reducing costs and expanding market access. E-commerce platforms facilitate online transactions, enabling farmers and agribusinesses to sell products nationally and internationally with greater ease. The use of digital analytics helps identify consumer behavior patterns and optimize marketing campaigns, enhancing return on investment.

Social media channels such as Facebook, Instagram, and WhatsApp have become essential tools for agribusinesses to showcase products, share success stories, and engage with consumers in real-time. Mobile apps designed specifically for agricultural marketing provide farmers with real-time market prices, weather updates, and direct communication with buyers, empowering them to make informed decisions. Additionally, digital marketing enables targeted advertising based on consumer demographics and preferences, improving cost efficiency and conversion rates.

1.2 Customer-Centric Marketing Approaches

Modern marketing in agribusiness is increasingly customer-focused, emphasizing the understanding of consumer needs and preferences. Market segmentation techniques categorize consumers based on demographics, psychographics, and buying behavior, enabling tailored product development and communication. There is a growing demand for organic, sustainable, and locally sourced products, prompting agribusinesses to adapt their offerings accordingly. Customer-centric strategies enhance product differentiation and build brand loyalty by aligning product attributes with consumer values.

In practice, agribusinesses conduct surveys, focus groups, and social listening to gather insights into consumer expectations. These insights inform product innovation, packaging design, and pricing strategies. For example, the rising trend of health-conscious consumers has led to the development of organic produce lines, gluten-free grains, and pesticide-free fruits, which are marketed with clear labeling and certification to build trust. Customizing marketing messages to resonate with different customer segments—such as urban millennials versus rural families—further strengthens engagement and loyalty.

1.3 Relationship Marketing and Partnerships

Relationship marketing prioritizes long-term engagement over transactional interactions. Agribusinesses foster trust and loyalty through consistent communication, personalized services, and collaborative initiatives. Partnerships with suppliers, distributors, community organizations, and customers strengthen the value chain and create shared benefits. Loyalty programs and community engagement activities are common tools to maintain customer retention, especially in rural markets where personal relationships influence purchasing decisions.

Collaborative models such as contract farming and cooperatives exemplify relationship marketing, where farmers and agribusiness firms share risks, costs, and benefits. These partnerships enhance supply reliability and quality assurance. Agribusinesses also engage in corporate social responsibility (CSR) initiatives that support local communities through education, infrastructure development, and environmental conservation, thereby reinforcing goodwill and brand reputation.

1.4 Integrated Marketing Communications (IMC)

IMC involves the strategic coordination of various marketing communication tools—advertising, public relations, sales promotions, personal selling, and direct marketing—to deliver a unified message. In agribusiness, IMC ensures consistent branding and reinforces product benefits, sustainability credentials, and quality assurances. This integrated approach maximizes resource efficiency and amplifies marketing impact across multiple channels, enhancing consumer trust and recognition.

For instance, an agribusiness marketing organic produce may combine social media campaigns, in-store promotions, press releases about sustainable farming practices, and direct email newsletters to educate consumers and stimulate demand. IMC also facilitates crisis communication, enabling agribusinesses to respond swiftly and transparently to issues such as product recalls or environmental incidents, preserving brand integrity.

1.5 Sustainable and Ethical Marketing

Sustainability has become a central theme in agribusiness marketing. Transparent communication about environmentally friendly practices, fair trade, and corporate social responsibility appeals to ethically conscious consumers and regulators. Marketing messages often highlight reduced pesticide use, water conservation, carbon footprint reduction, and social equity. Ethical marketing not only supports compliance with standards but also differentiates products in competitive markets, fostering long-term brand equity.

Certification schemes such as Fair Trade, Rainforest Alliance, and Organic labels are leveraged in marketing to signal commitment to ethical standards. Storytelling techniques that showcase farmer welfare, biodiversity conservation, and community development create emotional connections with consumers. Furthermore, agribusinesses integrate sustainability into product innovation by developing biodegradable packaging, reducing food waste through better supply chain management, and promoting circular economy practices.

ISSN: 3049-2289

Table 1: Contemporary Marketing Strategies in Agribusiness

Strategy	Description	Key Tools/Platforms	Impact on Agribusiness (%)	Benefits
Digital Marketing	Promotion via online platforms	Instagram, websites	20–50% increase in market reach	Direct customer engagement
Social Media Marketing	Real-time product promotion	WhatsApp groups	15–40% higher sales	Low-cost communication
E-commerce Platforms	Online selling of agri-products	Digital marketplaces	25–60% increase in income	Eliminates intermediaries
Branding & Certification	Organic, GI tagging	Labels and certifications	20–30% price premium	Consumer trust
Direct-to-Consumer (D2C)	Farmers sell directly	Farm apps, local delivery	30–70% profit increase	Better price realization
Value Addition	Processing and packaging	Agro-processing units	25–50% higher returns	Extended shelf life
Market Intelligence Systems	Price and demand forecasting	Mobile apps, AI tools	15–30% better decision-making	Risk reduction
Subscription Models	Regular delivery services	Weekly/monthly plans	10–25% stable income	Customer loyalty

2. Supply Chain Integration in Agribusiness

2.1 Importance of Supply Chain Integration

Agribusiness supply chains are inherently complex, involving multiple stakeholders such as input suppliers, farmers, processors, distributors, and retailers. Integration of these components enhances coordination, reduces redundancies, and improves responsiveness to market demands. Effective integration strengthens supply chain resilience, reduces lead times, and optimizes resource utilization, which is critical in perishable product management.

Integrated supply chains facilitate better communication and collaboration among participants, enabling synchronized planning and execution. This reduces bottlenecks, minimizes inventory holding costs, and improves overall supply chain visibility. In volatile markets, integration supports agility, allowing agribusinesses to respond promptly to changes in demand, weather conditions, and regulatory environments.

2.2 Vertical Integration

Vertical integration refers to the consolidation of multiple supply chain stages under a single organizational umbrella. Agribusiness firms adopting vertical integration can control production quality, reduce transaction costs, and secure supply and distribution channels. This approach facilitates better risk management and allows for strategic alignment of production with market requirements. However, it requires significant investment and management capability to handle diverse operations.

Examples include agribusiness conglomerates that own farms, processing plants,

ISSN: 3049-2289

packaging facilities, and retail outlets, enabling end-to-end control. Vertical integration supports traceability, essential for food safety and certification compliance. It also allows firms to implement uniform quality standards and sustainability practices across the supply chain, enhancing brand credibility.

2.3 Information Technology and Data Sharing

The adoption of advanced information technologies such as Enterprise Resource Planning (ERP), blockchain, and the Internet of Things (IoT) has transformed supply chain transparency and efficiency. Real-time data sharing among supply chain partners enhances inventory management, traceability, and quality control. Blockchain technology provides immutable records that improve trust and traceability, essential for food safety and certification. IoT devices monitor environmental conditions during storage and transport, reducing spoilage and ensuring compliance with standards.

ERP systems integrate procurement, production, inventory, and sales data, facilitating coordinated decision-making. Blockchain enables secure sharing of transaction records and certifications, reducing fraud and enhancing consumer confidence. IoT sensors track temperature, humidity, and location throughout the supply chain, alerting stakeholders to deviations that could compromise product quality. These technologies collectively improve supply chain visibility, enabling proactive interventions.

2.4 Collaborative Planning and Forecasting

Collaborative planning involves joint efforts among supply chain members to align production and distribution with market demand forecasts. Sharing accurate and timely data enables better inventory control, reduces waste, and prevents stockouts. Advanced analytics and machine learning models support demand forecasting, enabling agile supply chain responses. This collaboration fosters stronger partnerships and shared accountability across the supply chain.

By pooling data on sales trends, weather forecasts, and consumer behavior, supply chain partners can generate more accurate demand projections. This reduces the bullwhip effect—where small fluctuations in demand amplify upstream—leading to more stable production schedules and inventory levels. Collaborative planning also supports contingency strategies, mitigating risks posed by disruptions such as natural disasters or pandemics.

2.5 Logistics and Distribution Optimization

Efficient logistics and distribution systems are vital for maintaining product quality and minimizing costs in agribusiness. Integrated logistics management synchronizes transportation, warehousing, and cold chain operations to ensure timely delivery and reduce post-harvest losses. The use of route optimization software, temperature-controlled storage, and real-time tracking enhances operational efficiency. Integration facilitates responsiveness to market fluctuations and supports just-in-time delivery models.

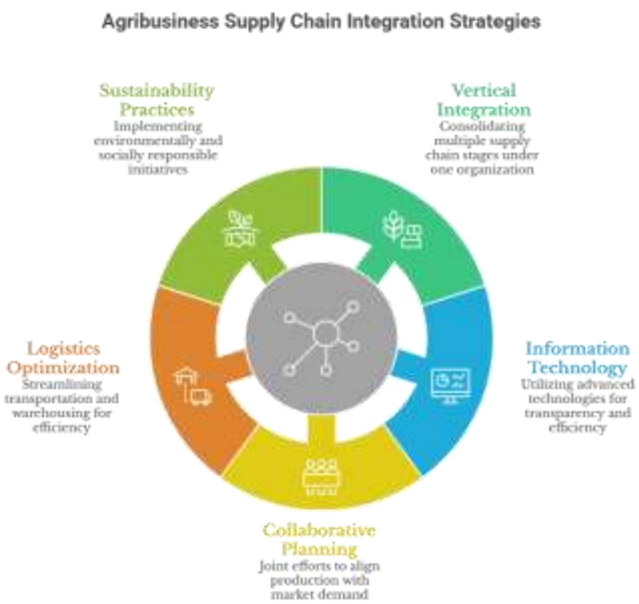
Cold chain logistics are particularly critical for perishable products such as fruits, vegetables, dairy, and meat. Maintaining optimal temperature and humidity levels throughout transportation and storage preserves freshness and extends shelf life. Advanced tracking systems provide end-to-end visibility, enabling quick response to delays or deviations. Additionally, centralized distribution centers reduce duplication of efforts and improve economies of scale.

2.6 Sustainability in Supply Chain

Sustainability practices are increasingly embedded in agribusiness supply chains to address environmental and social challenges. Initiatives include reducing greenhouse gas emissions, optimizing water use, minimizing packaging waste, and promoting fair labor practices. Sustainable supply chains contribute to regulatory compliance, risk mitigation, and enhanced corporate reputation. Lifecycle assessments and sustainability reporting are tools used to monitor and communicate supply chain impacts.

ISSN: 3049-2289

Agribusinesses implement renewable energy solutions, such as solar-powered cold storage, to reduce carbon footprints. Water-saving irrigation technologies and waste recycling programs further enhance environmental stewardship. Social sustainability involves ensuring safe working conditions, fair wages, and community development. Transparent reporting and third-party audits validate these efforts, strengthening stakeholder trust.



3. Synergistic Effects of Marketing and Supply Chain Integration

The convergence of contemporary marketing strategies with supply chain integration generates synergistic benefits. Digital marketing platforms provide real-time consumer insights that inform supply chain planning, enabling demand-driven production and distribution. Customer-centric approaches align product development with supply chain capabilities, enhancing responsiveness and reducing inefficiencies. Sustainable marketing messages are reinforced by transparent supply chain practices, building consumer trust and brand loyalty.

For example, an agribusiness promoting organic products through digital channels can leverage blockchain-enabled traceability to assure customers of product authenticity. Collaborative planning ensures that supply meets the specific preferences identified through targeted marketing. Integrated logistics guarantee timely delivery, supporting customer satisfaction. This alignment reduces operational costs, minimizes waste, and enhances competitive positioning.

4. Challenges and Future Directions

Despite the benefits, agribusinesses face challenges in implementing contemporary marketing and supply chain integration. Barriers include limited digital infrastructure in rural areas, fragmented supply chains, lack of skilled personnel, and resistance to change. Data privacy and cybersecurity concerns also pose risks in technology adoption.

Future directions involve leveraging artificial intelligence and big data analytics to enhance predictive capabilities, personalized marketing, and supply chain optimization. AI-powered tools can analyze vast datasets to forecast demand patterns, optimize routes, and customize marketing content. Blockchain adoption is expected to increase for improved transparency and trust. Emphasis on circular economy principles will drive sustainable marketing and supply chain innovations, such as waste valorization and resource recycling.

Policy support, capacity building, and cross-sector collaboration are critical enablers for the successful transformation of agribusiness. Governments and industry bodies can facilitate access to digital infrastructure, training programs, and financial incentives. Partnerships between technology providers, agribusinesses, and research institutions will foster innovation and knowledge exchange.

Conclusion

Contemporary marketing strategies combined with integrated supply chain management are pivotal for the success and sustainability of agribusiness in today's competitive environment. Digital marketing, customer-centric approaches, relationship building, integrated communications, and ethical marketing address evolving consumer demands and market dynamics. Supply chain integration through vertical

ISSN: 3049-2289

control, technological adoption, collaborative planning, logistics optimization, and sustainability practices enhances efficiency and resilience. Together, these strategies create a robust framework that supports agribusiness growth, innovation, and responsible stewardship of resources, positioning the sector to meet future challenges and opportunities effectively.

References

Chandrasekaran, N., & Raghuram, G. (2014). *Agribusiness supply chain management*. CRC Press.

Eskola, E. (2005). *Agricultural marketing and supply chain management in Tanzania: A case study* (Vol. 16). Dar es Salaam: Economic and Social Research Foundation.

Ganesh Kumar, C., Murugaiyan, P., & Madanmohan, G. J. I. I. M. (2017). Agri-food supply chain management: literature review. *Intelligent Information Management*, *9*, 68-96.

Kwamega, M., Li, D., & Abrokwah, E. (2018). Supply chain management practices and agribusiness firms' performance: Mediating role of supply chain integration. *South African Journal of Business Management*, *49*(1), 1-11.

Humphrey, J. (2006). Policy implications of trends in agribusiness value chains. *The European journal of development research*, *18*(4), 572-592.

Grunert, K. G., Fruensgaard Jeppesen, L., Risom Jespersen, K., Sonne, A. M., Hansen, K., Trondsen, T., & Young, J. A. (2005). Market orientation of value chains: A conceptual framework based on four case studies from the food industry. *European Journal of Marketing*, *39*(5-6), 428-455.

ISSN: 3049-2289

Bridging the Digital Divide: Challenges and Opportunities in ICT-Enabled Rural Extension Services

Isha* and Sumesh Sharma

Research Scholar, Department of Extension Education, College of Agriculture, Punjab Agricultural University, Ludhiana, Punjab, India

Research Scholar, Department of Agricultural Extension and Communication, College of Agriculture, Swami Keshwanand Rajasthan Agricultural University, Bikaner – 334006, Rajasthan

1.Introduction

Information and Communication Technologies (ICTs) have revolutionized various sectors globally, including agriculture and rural development. Rural extension services, which traditionally rely on face-to-face interactions to transfer agricultural knowledge and innovations to farmers, are increasingly adopting ICT tools to enhance their reach, efficiency, and impact. However, the digital divide the gap between those who have access to digital technologies and those who do not remains a critical barrier to the effective implementation of ICT-enabled rural extension services. This divide is often more pronounced in rural areas due to infrastructural, socio-economic, and cultural factors. Bridging this divide is essential to ensure equitable access to agricultural information, improve productivity, and promote sustainable rural livelihoods. This article explores the challenges and opportunities associated with ICT-enabled rural extension services, focusing on technological, socio-economic, infrastructural, and policy dimensions.

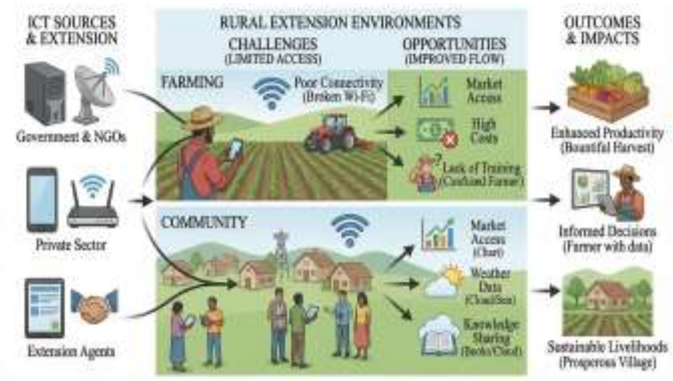


Figure 1: Conceptual Framework of ICT-Driven Rural Extension and Digital Inclusion

2. The Role of Rural Extension Services in Agricultural Development

Rural extension services play a pivotal role in agriculture by facilitating the transfer of knowledge, innovations, and best practices from research institutions to farmers. These services help farmers adopt improved seed varieties, pest and disease management techniques, soil conservation methods, and market information. Traditionally, extension services are delivered through in-person visits by extension agents, group meetings, and farmer field schools. Despite their importance, these traditional methods face challenges such as limited reach, inadequate resources, and delays in information dissemination.

ICTs offer transformative potential by enabling real-time communication, remote advisory services, and broader access to relevant information. They help overcome geographical barriers, reduce costs, and provide timely, customized advice. Integrating ICTs into rural extension systems can enhance knowledge dissemination, empower farmers, and stimulate innovation adoption.

3. Understanding the Digital Divide in Rural Contexts

The digital divide in rural areas encompasses disparities in access to digital devices, internet connectivity, digital literacy, and availability of relevant local content. Several factors contribute to this divide:

a) **Limited Infrastructure:** Many rural regions suffer from inadequate telecommunication

ISSN: 3049-2289

networks and unreliable electricity supply, constraining the use of digital technologies.

b) **Affordability Issues:** The high cost of smartphones, computers, and internet subscriptions relative to rural incomes limits technology adoption.

c) **Low Digital Literacy:** Many rural residents lack the skills and confidence to use digital tools effectively.

d) **Cultural and Language Barriers:** The absence of localized content in native languages and culturally appropriate formats reduces the relevance and usability of ICT services.

e) **Gender Disparities:** Women often face additional barriers to accessing and using digital technologies due to socio-cultural norms, lower literacy levels, and limited control over resources.

Addressing these interrelated factors is essential to bridge the digital divide and ensure inclusive access to ICT-enabled rural extension services.

4. ICT Tools and Platforms Used in Rural Extension Services

A variety of ICT tools have been integrated into rural extension services, each with unique advantages and challenges:

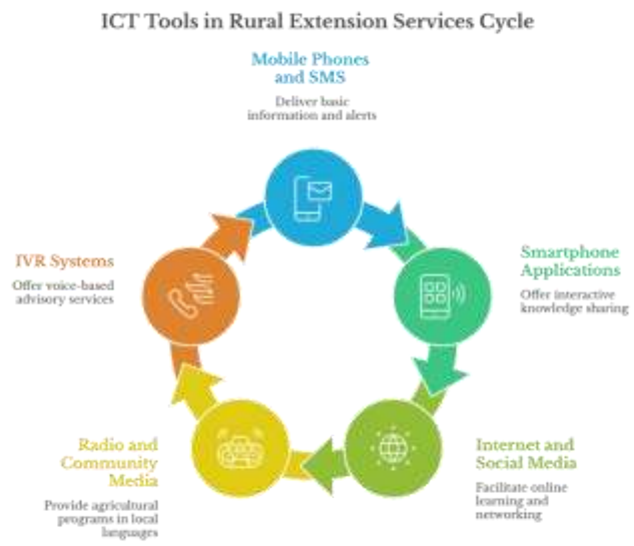
a) **Mobile Phones and SMS Services:** Mobile phones are the most widespread ICT tool in rural areas. SMS services deliver weather forecasts, market prices, pest and disease alerts, and advisory messages directly to farmers' phones. Their simplicity and low cost make them highly accessible.

b) **Smartphone Applications:** With the increasing penetration of smartphones, applications offer interactive platforms for knowledge sharing, diagnostic tools, and networking among farmers and experts. Apps can provide multimedia content, enhancing comprehension and engagement.

c) **Internet and Social Media:** Internet access enables farmers to explore online resources, watch video tutorials, participate in forums, and connect with agricultural experts. Social media platforms facilitate peer learning and community building.

d) **Radio and Community Media:** Radio remains a vital medium in areas with low digital penetration. Community radio stations broadcast agricultural programs in local languages, complementing digital tools.

e) **Interactive Voice Response (IVR) Systems:** IVR systems provide voice-based advisory services suitable for illiterate or semi-literate users, allowing farmers to access information via phone calls.



5. Challenges in Implementing ICT-Enabled Rural Extension Services

5.1 Infrastructure Limitations

Many rural areas lack reliable electricity and internet connectivity, limiting access to advanced ICT tools. Network coverage is often inconsistent, and broadband penetration remains low, restricting access to rich multimedia content and interactive services.

5.2 Socio-Economic Barriers

The cost of smartphones, data plans, and device maintenance is prohibitive for many smallholder farmers. Poverty also limits the ability to invest in complementary inputs such as quality seeds and

ISSN: 3049-2289

fertilizers, reducing the benefits derived from ICT-based information.

5.3 Digital Literacy and Capacity

Limited digital skills among rural populations hinder the effective use of ICT tools. Training programs are often insufficient, inaccessible, or not tailored to local needs, leading to underutilization of available technologies.

5.4 Content Relevance and Language Barriers

Extension content is frequently developed in dominant languages and may not consider local dialects or cultural contexts. Generic or technical messages may fail to address specific local challenges, reducing adoption.

5.5 Gender Inequality

Women farmers face additional hurdles due to socio-cultural norms restricting their access to digital devices and education. Lower literacy rates and limited control over household resources further deepen the gender digital divide, excluding women from ICT benefits.

5.6 Institutional and Policy Constraints

Fragmented extension systems, weak coordination among stakeholders, and lack of supportive policies impede the integration of ICTs. Issues related to data privacy, security, and sustainability of ICT initiatives also pose significant challenges.

Table 1: Challenges in ICT-Enabled Rural Extension Services

Challenge Category	Specific Issue	Underlying Cause	Impact on Farmers	Severity (Low/Medium/High)
Digital Infrastructure	Poor internet connectivity	Limited rural broadband	Restricted access to ICT tools	High
Digital Literacy	Lack of technical skills	Low education and training	Inability to use mobile apps/platforms	High
Economic Constraints	High cost of devices/data	Low income levels	Limited adoption of ICT tools	High
Language Barriers	Content not in local languages	Lack of localization	Misinterpretation of information	Medium
Gender Digital Divide	Limited access for women	Socio-cultural norms	Reduced participation of women farmers	High
Content Relevance	Generic advisories	Lack of location-specific data	Low usefulness of recommendations	Medium
Trust Deficit	Low confidence in digital advisories	Lack of validation	Poor adoption rates	Medium
Power Supply Issues	Unreliable electricity	Infrastructure gaps	Interrupted access to ICT services	High
Data Privacy Concerns	Misuse of farmer data	Weak regulations	Hesitation in using digital platforms	Medium

6. Opportunities Presented by ICT in Rural Extension

6.1 Enhanced Information Accessibility and Timeliness

ICTs enable rapid dissemination of up-to-date agricultural information, allowing farmers to make timely decisions about planting, pest management, and marketing, increasing productivity and reducing losses.

6.2 Cost-Effectiveness and Scalability

Digital platforms reduce the need for physical travel and human resources, enabling extension services to reach larger audiences at lower costs, improving efficiency and coverage.

6.3 Interactive and Personalized Advisory Services

Advanced ICT tools facilitate two-way communication, allowing farmers to ask questions, receive tailored advice, and share experiences with peers and experts, enhancing learning and problem-solving.

6.4 Real-Time Data Collection and Feedback Mechanisms

ICTs enable the collection of real-time data on crop conditions, pest outbreaks, and farmer needs, improving monitoring, evaluation, and responsiveness of extension programs.

6.5 Empowerment and Inclusion

ICTs can empower marginalized groups by improving access to information, fostering social capital, and facilitating participation in decision-making processes when designed inclusively.

6.6 Integration with Other Rural Development Initiatives

ICT-enabled extension services can be linked with financial services, input supply chains, and market platforms, creating integrated value chains that enhance rural livelihoods.

7. Strategies to Bridge the Digital Divide in Rural Extension

7.1 Infrastructure Development

Investing in rural broadband expansion, solar-powered charging stations, and affordable digital devices is critical to improving access to ICTs in underserved areas.

7.2 Capacity Building and Digital Literacy

Comprehensive training programs tailored to farmers, extension agents, and community leaders improve digital skills, confidence, and effective use of ICT tools.

7.3 Content Localization and Cultural Sensitivity

Developing extension content in local languages, using audio-visual formats, and integrating indigenous knowledge make ICT services more relevant and accessible.

7.4 Gender-Sensitive Approaches

Designing ICT interventions that address women's specific needs, promoting women's digital literacy, and ensuring equitable access help reduce gender disparities.

7.5 Multi-Stakeholder Collaboration

Partnerships among governments, private sector, NGOs, and farmer organizations mobilize resources, foster innovation, and enhance scalability and sustainability of ICT initiatives.

7.6 Policy and Regulatory Support

Formulating supportive policies on ICT infrastructure, data governance, funding, and capacity building creates an enabling environment for sustainable ICT-enabled extension services.

7.7 Monitoring, Evaluation, and Adaptive Management

Implementing robust frameworks to assess impact, gather user feedback, and adapt interventions ensures continuous improvement and relevance of ICT-based extension programs.

ISSN: 3049-2289

8. Case Examples of ICT-Enabled Rural Extension Success

a) **Mobile-Based Advisory Services:** Programs delivering localized weather forecasts and pest alerts via SMS have improved crop management and reduced losses in various countries.

b) **Farmer Helplines:** Interactive call centers provide real-time expert advice, overcoming literacy barriers through voice communication, and enhancing problem-solving capacity.

c) **Digital Farmer Forums:** Online platforms facilitate peer-to-peer learning, collective problem-solving, and social networking, strengthening community resilience.

d) **E-Agriculture Portals:** Comprehensive websites aggregate information on best practices, input suppliers, and market trends, supporting informed decision-making.

These examples highlight the potential of context-specific ICT solutions to enhance rural extension effectiveness and farmer empowerment.

9. Emerging Trends and Innovations in ICT for Rural Extension

a) **Artificial Intelligence (AI) and Machine Learning:** AI-driven tools offer predictive analytics for pest outbreaks, yield forecasting, and personalized advisory services.

b) **Unmanned Aerial Vehicles (Drones):** Drones facilitate remote sensing for crop monitoring, disease detection, and precision agriculture.

c) **Blockchain Technology:** Enhances transparency, traceability, and trust in agricultural value chains.

d) **Internet of Things (IoT):** Sensor networks provide real-time environmental data, enabling adaptive management and resource optimization.

e) **Gamification and Virtual Reality (VR):** Interactive learning experiences engage farmers, improving knowledge retention and application.

10. Conclusion

ICT-enabled rural extension services hold transformative potential to enhance agricultural productivity, sustainability, and rural livelihoods. However, the persistent digital divide poses significant challenges that must be addressed through integrated efforts encompassing infrastructure development, capacity building, content localization, gender inclusion, and enabling policies. Multi-stakeholder partnerships and emerging technologies can accelerate progress toward inclusive, effective, and sustainable rural extension systems. Bridging the digital divide is not only a technological challenge but also a socio-economic and institutional imperative vital for empowering rural communities and achieving broader development goals.

References

Khatri, A., Lallawmkimi, M. C., Rana, P., Panigrahi, C. K., Minj, A., Koushal, S., & Ali, M. U. (2024). Integration of ICT in agricultural extension services: A review. *Journal of Experimental Agriculture International*, *46*(12), 394-410.

Mohanty, P. C. (2008, August). Bridging digital divide: The role of ICT for rural development in India. In *2008 International Symposium on Information Technology* (Vol. 2, pp. 1-12). IEEE.

Ponge, A. (2016). Bridging the gender digital divide: Challenges in access and utilization of ICTs for development at the devolved level in Kenya. *International Journal of Innovative Research and Development*, *5*(7), 328-339.

Upadhyaya, L., Burman, R. R., Sangeetha, V., Lenin, V., Sharma, J. P., & Dash, S. (2019). Digital Inclusion: Strategies to Bridge Digital Divide in Farming Community. *Journal of Agricultural Science & Technology*, *21*(5).

Barber, J., Mangnus, E., & Bitzer, V. (2018). Harnessing ICT for agricultural extension. *Europe*, *91*(120.6), 31-35.

AGRICULTURE BULLETIN
ISSN: 3049-2289

Biofertilizers in Modern Nutrient Management Strategies

Manu Shashwat, Sangeeta Kumari, Pankhuri Raj, and Aman Nagar
Research Scholar, Acharya Narendra Deva University of Agriculture and Technology, Kumarganj, Ayodhya, Uttar Pradesh, India
Research Scholar, Department of Botany, Dr. Shyama Prasad Mukherjee University, Ranchi, Jharkhand, India
Research Scholar, Department of Soil Science, Dr. Rajendra Prasad Central Agricultural University, Pusa, Bihar, India
Research Scholar, Department of Soil Science, ICAR- Indian Agricultural Research Institute, Karnal Hub, India

1.Introduction

Sustainable agriculture faces the dual challenge of increasing food production to meet global demand while minimizing environmental impact. Conventional agriculture heavily relies on synthetic chemical fertilizers, which, despite boosting yields, often lead to environmental degradation, including water pollution, greenhouse gas emissions, and soil health decline. Biofertilizers and microbial inoculants offer a promising alternative by harnessing the power of beneficial microorganisms to enhance nutrient availability and uptake in plants. These biological products represent an eco-friendly approach to nutrient management, promoting soil fertility, plant growth, and overall ecosystem health. This chapter delves into the types, mechanisms, applications, and benefits of biofertilizers and microbial inoculants, highlighting their role in transitioning towards more sustainable agricultural practices.

2. Understanding Biofertilizers and Microbial Inoculants

Biofertilizers are preparations containing living microorganisms that, when applied to seeds, plant surfaces, or soil, colonize the rhizosphere or the interior of the plant and promote growth by increasing the supply or availability of primary nutrients to the host plant. Microbial inoculants is a broader term often used interchangeably, referring to any preparation containing microorganisms intended to introduce or increase a microbial population in a specific environment for a beneficial purpose.

2.1 Types of Biofertilizers and Microbial Inoculants

Biofertilizers can be broadly categorized based on the primary nutrient they help make available or the type of microorganism involved:

a) **Nitrogen-fixing Biofertilizers:** These include bacteria that convert atmospheric nitrogen (N_2) into ammonia (NH_3), a form usable by plants.
   i. **Symbiotic Nitrogen Fixers:** *Rhizobium* species (for legumes), *Frankia* (for actinorhizal plants).
   ii. **Free-living Nitrogen Fixers:** *Azotobacter*, *Azospirillum* (in aerobic conditions), *Clostridium*, *Anabaena* (in anaerobic or aquatic conditions).

b) **Phosphate-solubilizing Biofertilizers (PSB):** These microorganisms solubilize insoluble inorganic phosphate compounds (e.g., tricalcium phosphate, rock phosphate) into plant-available forms like orthophosphate.
   i. **Bacteria:** *Bacillus*, *Pseudomonas*.
   ii. **Fungi:** *Aspergillus*, *Penicillium*.

c) **Potassium-solubilizing Biofertilizers (KSB):** These microbes release potassium from insoluble mineral forms into soluble forms.
   i. **Bacteria:** *Bacillus mucilaginosus*, *Frateuria aurantia*.

ISSN: 3049-2289

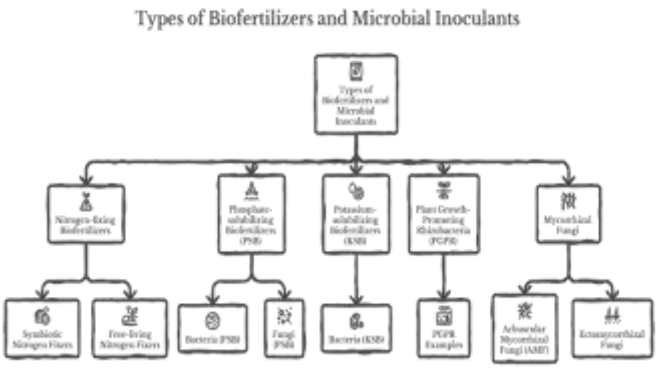
d) **Plant Growth-Promoting Rhizobacteria (PGPR):** A diverse group of bacteria that colonize plant roots and promote growth through various direct and indirect mechanisms, including nutrient solubilization, hormone production, and disease suppression.

   i. *Pseudomonas*, *Bacillus*, *Azospirillum*.

e) **Mycorrhizal Fungi:** These fungi form symbiotic associations with plant roots, extending the root system's reach and enhancing the uptake of water and nutrients, particularly phosphorus.

   i. **Arbuscular Mycorrhizal Fungi (AMF):** *Glomus*, *Acaulospora*.

   ii. **Ectomycorrhizal Fungi:** *Boletus*, *Amanita*.



3. Mechanisms of Action

The beneficial effects of biofertilizers and microbial inoculants stem from several key mechanisms:

3.1 Nitrogen Fixation

Nitrogen-fixing microorganisms possess the enzyme nitrogenase, which catalyzes the conversion of atmospheric N2 into NH3. This process is crucial because atmospheric N2 is abundant but biologically unavailable to plants.

- **Symbiotic Nitrogen Fixation:** *Rhizobium* bacteria infect legume roots, forming nodules where they fix nitrogen. The plant provides carbohydrates to the bacteria, and in return, receives fixed nitrogen. This is a highly efficient process, significantly reducing the need for synthetic nitrogen fertilizers.
- **Free-living Nitrogen Fixation:** Microorganisms like *Azotobacter* and *Azospirillum* live freely in the soil or associate loosely with plant roots, fixing nitrogen independently. While less efficient than symbiotic fixation, they still contribute substantially to the soil's nitrogen pool.

3.2 Phosphate Solubilization and Mobilization

Phosphorus is often abundant in soil but mostly in insoluble forms unavailable to plants. PSB release organic acids (e.g., gluconic acid, lactic acid) and phosphatases that convert insoluble phosphate into soluble orthophosphate ions.

- **Organic Acid Production:** These acids chelate cations (like Ca, Fe, Al) bound to phosphate, releasing the phosphate into the soil solution.
- **Enzyme Production:** Phosphatase enzymes hydrolyze organic phosphate compounds, making inorganic phosphate available.
- **Mycorrhizal Mobilization:** Mycorrhizal fungi extend their hyphae far beyond the plant roots, increasing the surface area for nutrient absorption, particularly for less mobile nutrients like phosphorus. They actively transport phosphate from the soil to the plant.

3.3 Potassium Solubilization

Similar to phosphate, a large fraction of potassium in soil exists in insoluble mineral forms (e.g., feldspar, mica). KSB release organic acids and enzymes that break down these minerals, releasing soluble potassium ions for plant uptake.

3.4 Production of Plant Growth-Promoting Substances

Many PGPR produce phytohormones (e.g., auxins, gibberellins, cytokinins) that directly stimulate plant growth by promoting cell division, elongation, and differentiation. They can also produce vitamins, amino acids, and other growth factors.

ISSN: 3049-2289

3.5 Enhanced Nutrient Uptake

Beyond making nutrients available, some microbial inoculants improve the plant's ability to absorb these nutrients. Mycorrhizal fungi, for instance, significantly increase the root surface area, enhancing the uptake of water and various nutrients (P, N, Zn, Cu).

3.6 Biocontrol and Stress Tolerance

While not directly related to nutrient provision, many beneficial microbes also offer indirect benefits by suppressing plant pathogens and inducing systemic resistance in plants. They can also help plants cope with abiotic stresses like drought, salinity, and heavy metal toxicity, indirectly improving nutrient use efficiency by maintaining plant health.

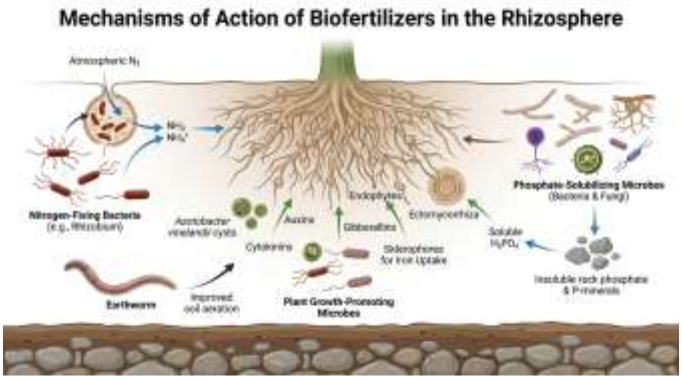


Figure 1: Mechanisms of Action of Biofertilizers

4. Application Methods

Effective application of biofertilizers and microbial inoculants is crucial for their success. Common methods include:

a) **Seed Treatment:** Seeds are coated with a microbial formulation before sowing. This is a cost-effective method that ensures early colonization of the rhizosphere.

b) **Soil Application:** Biofertilizers can be mixed with soil, compost, or farmyard manure and applied directly to the field. This method is suitable for established crops or when a broader distribution of microbes is desired.

c) **Seedling Root Dip:** For transplanted crops, the roots of seedlings are dipped in a microbial suspension before planting. This ensures direct contact and colonization.

d) **Foliar Spray:** Some liquid formulations can be sprayed directly onto plant leaves, though this is less common for soil-borne nutrient-cycling microbes.

e) **Drip Irrigation:** Liquid formulations can be introduced through irrigation systems, allowing for precise delivery to the root zone.

Table 1: Common Application Methods for Biofertilizers

Application Method	Description	Advantages	Disadvantages
Seed Treatment	Coating seeds with microbial formulation	Cost-effective, early colonization	Limited microbial survival, uneven distribution
Soil Application	Mixing with soil/compost and applying to field	Broad distribution, suitable for established crops	Higher cost, potential for microbial competition
Seedling Root Dip	Dipping seedling roots in microbial suspension	Direct colonization, high success rate	Labor-intensive, specific to transplanted crops
Drip Irrigation	Introducing liquid formulation via irrigation	Uniform delivery, efficient water use	Requires specialized equipment

5. Benefits of Biofertilizers and Microbial Inoculants

The adoption of biofertilizers and microbial inoculants offers a multitude of benefits for agriculture and the environment:

5.1 Enhanced Crop Yield and Quality

By improving nutrient availability and uptake, biofertilizers directly contribute to increased crop yields. They also enhance the nutritional quality of

ISSN: 3049-2289

produce by improving nutrient content and sometimes even flavor.

5.2 Reduced Reliance on Chemical Fertilizers

Biofertilizers can significantly reduce the need for synthetic fertilizers, especially nitrogen and phosphorus. This translates to lower input costs for farmers and reduced environmental pollution associated with chemical fertilizer production and use.

5.3 Improved Soil Health

Microbial inoculants contribute to building healthy soil ecosystems. They enhance soil structure, increase organic matter content (indirectly, by promoting plant growth and biomass input), and foster a diverse and active microbial community, leading to better soil aggregation, water infiltration, and aeration.

5.4 Environmental Sustainability

a) **Reduced Nutrient Leaching:** By making nutrients more available and improving plant uptake efficiency, biofertilizers minimize nutrient losses to groundwater and surface water bodies, preventing eutrophication.

b) **Lower Greenhouse Gas Emissions:** The production of synthetic nitrogen fertilizers is energy-intensive and a significant source of greenhouse gases (N2O). Reducing their use through biofertilizers helps mitigate climate change.

c) **Reduced Chemical Residues:** Biofertilizers are natural and leave no harmful residues in the soil or produce, making them ideal for organic farming and sustainable food systems.

5.5 Increased Plant Tolerance to Stress

Many beneficial microbes can induce systemic resistance in plants against pathogens and pests. They also help plants cope with abiotic stresses such as drought, salinity, and heavy metal toxicity by improving water and nutrient acquisition, producing osmoprotectants, or detoxifying harmful compounds.

6. Factors Affecting Efficacy

The successful application of biofertilizers and microbial inoculants is influenced by several factors:

6.1 Environmental Conditions

a) **Soil pH:** Each microorganism has an optimal pH range for activity. Extremes in pH can inhibit microbial growth and function.

b) **Soil Moisture and Temperature:** Adequate moisture is essential for microbial survival and activity. Extreme temperatures (too hot or too cold) can reduce viability.

c) **Soil Type:** Soil texture, organic matter content, and nutrient status can influence microbial colonization and efficacy. For instance, high organic matter can provide a better habitat for microbes.

6.2 Microbial Strain and Formulation

a) **Strain Specificity:** The effectiveness of a biofertilizer often depends on the specific microbial strain used, as different strains may have varying efficiencies in nutrient solubilization or nitrogen fixation.

b) **Formulation Quality:** The carrier material (e.g., peat, vermiculite, liquid), shelf life, and concentration of viable microbes in the formulation are critical for product efficacy.

c) **Compatibility:** Biofertilizers must be compatible with other agricultural inputs (e.g., pesticides, fungicides) to avoid negative interactions.

6.3 Crop Type and Management Practices

a) **Host Specificity:** Some symbiotic biofertilizers (e.g., *Rhizobium*) are highly host-specific, meaning a particular strain works only with certain legume species.

b) **Agronomic Practices:** Tillage practices, irrigation, and nutrient management strategies can all influence the survival and performance of inoculated microbes. For example, excessive tillage can disrupt microbial habitats.

7. Challenges and Future Perspectives

Despite their significant potential, biofertilizers and microbial inoculants face several challenges:

7.1 Quality Control and Standardization

Variability in product quality, viable cell count, and efficacy remains a major concern. Lack of stringent quality control measures can lead to inconsistent results and farmer distrust. Standardization of production and testing protocols is crucial.

7.2 Storage and Shelf Life

Many microbial products have a limited shelf life and require specific storage conditions (e.g., refrigeration) to maintain viability, which can be challenging in rural areas with limited infrastructure.

7.3 Environmental Variability

The performance of biofertilizers can be inconsistent across different soil types, climates, and farming systems, making it difficult to predict their effectiveness in diverse agricultural settings.

7.4 Farmer Adoption

Lack of awareness, perceived risks, and insufficient technical support can hinder widespread adoption by farmers, particularly in developing countries.

7.5 Future Directions

a) **Strain Improvement:** Genetic engineering and advanced breeding techniques can develop more robust and efficient microbial strains.

b) **Advanced Formulations:** Developing novel formulations (e.g., encapsulated microbes, co-inoculants) that enhance microbial survival, shelf life, and efficacy under diverse field conditions.

c) **Integrated Nutrient Management:** Biofertilizers are best utilized as part of an integrated nutrient management strategy, combining them with judicious use of organic and chemical fertilizers to optimize nutrient cycling and minimize environmental impact.

d) **Precision Agriculture:** Tailoring biofertilizer application based on specific soil and crop needs, leveraging technologies like remote sensing and soil mapping.

8. Conclusion

Biofertilizers and microbial inoculants are powerful tools in sustainable nutrient management, offering an environmentally friendly and economically viable alternative to conventional chemical fertilizers. By harnessing the natural capabilities of beneficial microorganisms, they enhance nutrient availability, promote plant growth, improve soil health, and reduce the environmental footprint of agriculture. While challenges related to quality control, storage, and environmental variability persist, ongoing research and technological advancements are paving the way for more effective and widely adopted microbial solutions. Integrating biofertilizers into comprehensive nutrient management strategies is crucial for building resilient agroecosystems that can meet the demands of a growing global population while safeguarding our planet.

References

Gulshan, T., Verma, A., Ayoub, L., Sharma, J., Sharma, T., Bhadu, A., & Singh, B. (2022). Increasing nutrient use efficiency in crops through biofertilizers. *The Pharma Innovation Journal*, *11*(6), 2003-2010.

Chaudhary, P., Singh, S., Chaudhary, A., Sharma, A. and Kumar, G., 2022. Overview of biofertilizers in crop production and stress management for sustainable agriculture. *Frontiers in plant science*, *13*, p.930340.

Soni, S.K., Manhas, R., Jakhar, Y., Sharma, A. and Soni, R., 2022. Biofertilizers for sustainable agriculture: current trends and future perspective. *Genomic, Proteomics, and Biotechnology*, pp.331-356.

Chakraborty, T. and Akhtar, N., 2021. Biofertilizers: prospects and challenges for future. *Biofertilizers: study and impact*, pp.575-590.

Mitter, E.K., Tosi, M., Obregón, D., Dunfield, K.E. and Germida, J.J., 2021. Rethinking crop nutrition in times of modern microbiology: innovative biofertilizer technologies. *Frontiers in Sustainable Food Systems*, *5*, p.606815.

AGRICULTURE BULLETIN
ISSN: 3049-2289

Integrated Nutrient Management (INM)

Ajit Kumar Meena*[1] , B.L.Mina[1], L.C. Malav[1]
[1]ICAR-NBSS&LUP, Regional Centre, Udaipur, Rajasthan, India

1.Introduction

Integrated Nutrient Management (INM) is a sustainable approach in agriculture that involves the judicious use of chemical fertilizers, organic manures, and bio-fertilizers to maintain soil fertility and enhance crop productivity. INM focuses on maintaining an optimum level of plant nutrients for achieving desired crop yield without degrading soil health.

Integrated Nutrient Management (INM) is defined as:"The maintenance or adjustment of soil fertility and plant nutrient supply at an optimum level to sustain desired crop productivity through the combined use of organic, inorganic, and biological sources."

Objectives of INM

- Increase crop yield
- Improve crop quality
- Increase farm income
- Sustain soil fertility
- Reduce environmental pollution

Concept of IPNSS (Integrated Plant Nutrient Supply System)-*IPNSS is a system that ensures balanced and continuous nutrient supply to crops through integration of organic, inorganic and biological sources for sustainable agriculture.* Crops continuously remove nutrients from the soil. Soil alone cannot supply nutrients indefinitely. Therefore, external nutrient supply is essential to maintain soil fertility and crop productivity

Issues in Adoption of INM

1. Lack of composting facilities
2. Limited availability of green manure seeds
3. Low adoption of bio-fertilizers
4. Insufficient production units
5. Weak linkage between soil testing labs & farmers
6. Poor extension services

Sources of INM

Chemical Fertilizers

- ❖ Provide nutrients in concentrated form ,
- ❖ Fast response in crop growth ,
- ❖ Low use efficiency (N: 20–35%, P: 15–25%) ,
- ❖ Excess use → soil degradation & pollution

ISSN: 3049-2289

Sources of INM- Chemical Fertilizers

Organic Manures

- Improve soil structure, aeration, and water holding capacity
- Supply macro + micro nutrients
- Enhance microbial activity
- India generates ~875 million tonnes organic waste annually
- Only ~60% used in agriculture

Green Manuring

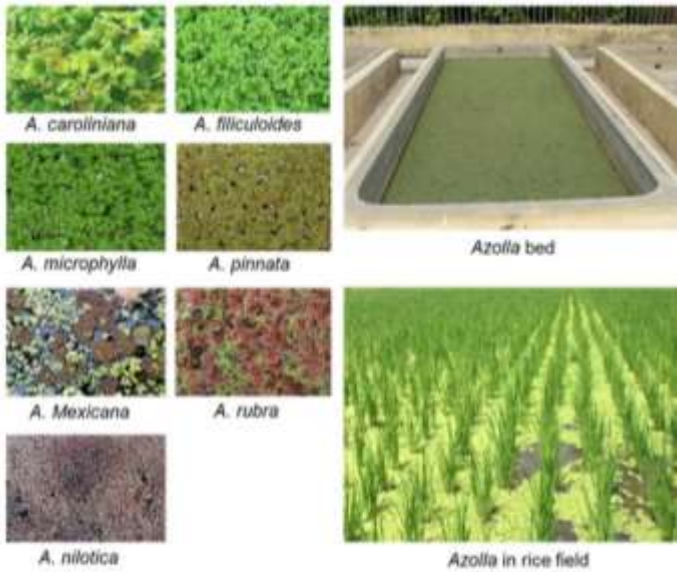
- Crops like **Dhaincha, Cowpea** grown and incorporated
- Adds organic matter and nitrogen
- Improves soil fertility

Bio-fertilizers

Bio-fertilizers contain **living microorganisms** that enhance nutrient availability.

Types

- Symbiotic: Rhizobium, Azolla
- Free living: Azotobacter, Blue Green Algae
- Associative: Azospirillum
- Phosphorus solubilizers: Bacillus, Pseudomonas



Benefits of Bio-fertilizers

- Biological nitrogen fixation
- Reduce chemical fertilizer requirement
- Improve soil health
- Eco-friendly & cost-effective
- Increase crop yield

Cropping Systems in INM

- Multiple Cropping
- Apply fertilizers crop-wise
- Legumes reduce nitrogen requirement
- Organic manure improves efficiency

◆ **Intercropping**

- Balanced fertilizer use
- Efficient nutrient utilization

◆ **Cereal–Legume System**

- Nitrogen applied mainly to cereals

ISSN: 3049-2289

- Legumes fix atmospheric nitrogen

Advantages of INM

- Increases net returns
- Reduces production cost
- Minimizes environmental pollution
- Improves fertilizer use efficiency
- Ensures sustainable agriculture

Conclusion

Integrated Nutrient Management is a scientifically proven sustainable approach that ensures:

- Long-term soil fertility
- Balanced nutrient supply
- Environmental protection
- Higher and stable crop productivity

INM Model:

```
                 Soil
            /     |      \
Organic     Chemical     Bio-fertilizers
   |           |               |
------ ------ ------ ------ Crop ------ ------ -------
                  |
                Yield ↑
```

AGRICULTURE BULLETIN
ISSN: 3049-2289

AI Revolutionizes Plant Disease Detection: Saving Crops with Smart Tech

Deepika T[1], Akshayasri M[2], Radha Krishnan G[2]
[1-] Ph.D Scholar, Department of Plant Pathology, Faculty of Agriculture, Chidambaram-608002
[2-] Research Scholar, Division of Genetics and Tree Improvement, ICFRE-Institute of Forest Genetics and Tree Breeding, Coimbatore-641002

Introduction

AI is revolutionizing plant disease detection, turning smart phones, drones, and sensors into powerful allies for farmers battling invisible threats to crops. Drawing from the detailed research article on AI-powered innovations, this expanded 3-page-style popular article dives deeper into how these technologies are saving harvests, boosting yields, and securing food for the world especially relevant for Indian agriculture pros like seed scientists facing real-field challenges.

The Hidden Crisis: Why Plant Diseases Are Agriculture's Silent Killer

Plant pathogens cause massive crop losses, wiping out 30-40% of potential yields annually and costing billions in damages. Traditional methods like microscopy, ELISA, and PCR are slow, expensive, and need expert skills, often failing to catch early or low-level infections. In countries like India, where agriculture feeds millions, timely detection is vital amid climate change and global trade spreading new threats. These traditional techniques struggle with uneven pathogen distribution and latent infections, delaying action until outbreaks hit hard. AI steps in here, offering speed, scale, and accuracy that humans alone can't match. Imagine a farmer in Tamil Nadu watching his coffee plants wither from wilt disease, or a wheat field in Uttar Pradesh ravaged by stem rust scenarios all too common, costing global agriculture 30-40% of potential yields yearly, or hundreds of billions in losses. Instruments like microscopy demand eagle-eyed experts peering through lenses for hours, often missing subtle signs. ELISA tests, while quicker, falter with false negatives and pricey antibodies not tuned for every local strain. PCR shines in labs for its sensitivity but flops in fields—too slow, costly, and lab-bound for a grower needing answers now. Climate change worsens this: warmer temps and trade routes supercharge outbreaks, hitting vulnerable spots like India hardest, where food security hangs on healthy crops.

AI's Toolkit: From Machine Learning to Drones

Machine learning models like Support Vector Machines (SVM) and Random Forests classify diseases from leaf images with up to 98% accuracy, far better than manual checks. Convolutional Neural Networks (CNNs) scan photos for symptoms, trained on datasets like PlantVillage, spotting issues in tomatoes, chilies and more crops. Drones and satellites provide aerial views for large farms, using computer vision to map outbreaks in real-time and guide targeted sprays. Smart sensors via IoT track humidity, soil moisture, and more, feeding data to AI for early alerts on phones. Support Vector Machines (SVM) slice through leaf image chaos with RBF kernels, nailing 98.48% accuracy on brinjal diseases or 87% on stems—beating humans at pattern-spotting. Random Forests thrive on big, messy datasets, hitting 79% on complex cases by voting across decision trees for robust calls. Convolutional Neural Networks (CNNs) devour Plant Village photos (healthy vs. diseased leaves from 14 crops), extracting features like spots or wilts via layers of filters. Custom CNNs with dilated convolutions and attention mechanisms push mean average precision to 99.80%, running lightweight on phones. Transfer learning from VGG-16 or ResNet-50 adapts these to new crops like chilies or potatoes with minimal retraining. Recurrent Neural Networks (RNNs) and LSTMs forecast outbreaks by crunching weather histories capturing how humidity spikes trigger rust weeks later. Unsupervised learning clusters anomalies, sniffing out novel pathogens without labels.

Technique	How It Works	Accuracy Boost	Farm Win
SVM	Maps data to hyperplanes for classification	98% on brinjal	Quick stem checks
CNNs	Layers detect edges, textures in images	99.8% MAP	Leaf snap diagnosis
Random Forest	Ensemble trees handle noisy data	79-90% across veggies	Scalable for big fields
LSTMs	Remembers long-term patterns	Predicts delayed outbreaks	Proactive spraying
Drones + CV	Aerial multispectral scans	Early blight in rice/grapes	Covers 100s of acres fast

Apps, Greenhouses and Edge Devices for Farmers

Apps like Plantix let grower snap a potato leaf, getting 90-100% accurate pest/disease IDs for maize or okraoutpacing local experts (40-58%). Nuru crushes cassava viral foes at 65-88% (multiple leaves), even teaching users better diagnostics over time. Newer ones like mPD-App hit 93.9% on 14 diseases. Smart greenhouses wire up IoT sensors for temp, humidity, CO2AI (via ANFIS or CNNs) auto-tweaks vents, lights, irrigation via apps like Blynk. Solar-powered, hack-proof, they yield more with less water/pesticides.

Farmers hurdles in switching to AI

Small, lab-biased datasets flop in muddy fields, models generalize poorly across climates or unseen diseases. Black-box decisions erode trust farmers need explainable AI showing "why this leaf is sick." Biases from imbalanced data hit smallholders hardest, plus privacy worries over shared field snaps. AI-IoT hives for real-time global nets, predicting climate-fueled outbreaks, even recovery forecasts post-infection. Open-source, farmer-friendly kits think free apps tuned for Indian staples plus interdisciplinary teams of pathologists, coders, and economists.

Reference

Sharma S, Vardhan M (2024). Enhanced Plant Disease Detection Using a Custom DOI: 10.1109/icccnt61001.2024.10725398

Sathya R et al. (2023). Vision Based Plant Leaf Disease Detection. Using Machine Learning Techniques. DOI: 10.1109/iceca58529.2023.10395620

Akbar MJU et al. (2023). Plant Stem Disease Detection Using Machine Learning Approaches. DOI: 10.1109/icccnt56998.2023.10307074

AGRICULTURE BULLETIN
ISSN: 3049-2289

Interactions among three Tritrophic levels: Plants, Pests and Natural Enemies

Dr Keshav Mehra[1] , Dr Veer Singh[2] and Dr Rajendra Kumar[3]
[1] Assistant Professor (Entomology), College of Agriculture, Hindoli-Bundi (AU, Kota)
[2] Professor (Entomology), College of Agriculture, Bikaner (SKRAU, Bikaner)
[3] Assistant Professor (Entomology), Apex Institute of Agriculture and Research, Kota

Introduction

Agricultural ecosystems are highly dynamic and involve complex biological interactions among different organisms. Traditionally, pest management focused only on the interaction between plants and insect pests. However, modern ecological understanding recognizes the importance of a third level-natural enemies, which include predators and parasitoids.

The interaction among plants, herbivorous insects (pests), and natural enemies is referred to as tritrophic interaction. These interactions are essential for maintaining ecological balance and form the scientific basis for biological control and Integrated Pest Management (IPM) strategies. Tritrophic interactions highlight that plants are not passive victims of herbivory. Instead, they actively respond to pest attacks by producing defensive chemicals and signals that indirectly recruit natural enemies. This ecological mechanism reduces pest populations naturally and contributes to sustainable agriculture.

Concept of Tritrophic Interaction

The term *trophic* refers to feeding levels in an ecosystem. A tritrophic system includes three distinct levels:

1. **First Trophic Level (Producers):** Plants that produce food through photosynthesis
2. **Second Trophic Level (Herbivores):** Insect pests that feed on plants
3. **Third Trophic Level (Natural Enemies):** Predators and parasitoids that feed on herbivores

This system is interconnected, where a change at one level affects the others. For example, increased pest attack can stimulate plant defenses, which in turn attract more natural enemies.

Role of Plants in Tritrophic Interactions

Plants play an active and central role in tritrophic interactions through various defense strategies. These defenses are broadly classified into direct and indirect mechanisms.

Direct Defense Mechanisms

Direct defenses reduce damage by affecting herbivores directly:

- **Chemical Defenses:** Plants produce secondary metabolites such as alkaloids, phenolics, and terpenoids that are toxic or deterrent to insects.
- **Physical Defenses:** Special structures like thorns, spines, trichomes (hair-like structures), and thick cuticles prevent feeding.
- **Digestibility Reduction:** Some plants produce compounds that interfere with digestion in herbivores.

Indirect Defense Mechanisms

Indirect defenses involve attracting natural enemies of herbivores:

- Plants release Herbivore-Induced Plant Volatiles (HIPVs) when attacked.
- These chemicals serve as signals to attract predators and parasitoids.

ISSN: 3049-2289

- Natural enemies use these cues to locate their prey or host insects.

Plant Signaling and Communication

Plants can:

- Communicate with neighboring plants through airborne signals
- Activate defense genes in advance
- Exhibit systemic responses throughout the plant

This advanced signaling system enhances plant survival and ecological interactions.

Role of Herbivores (Insect Pests)

Herbivores act as a bridge between plants and natural enemies.

Feeding Behavior- Herbivores damage plant tissues by chewing, sucking, or boring, Feeding triggers plant defense responses

Influence on Plant Responses- Different herbivores induce different chemical signals

For example: Chewing insects (caterpillars) induce strong volatile emissions and sap-sucking insects (aphids) trigger different responses

Herbivore Adaptations

- Detoxification of plant chemicals
- Behavioral avoidance of plant defenses
- Rapid reproduction to escape predation

Thus, herbivores continuously evolve to overcome plant defenses.

Role of Natural Enemies

Natural enemies form the third trophic level and are crucial for biological pest control.

Types of Natural Enemies

Predators- Consume multiple prey during their lifetime. Eg. Ladybird beetles, spiders, lacewings

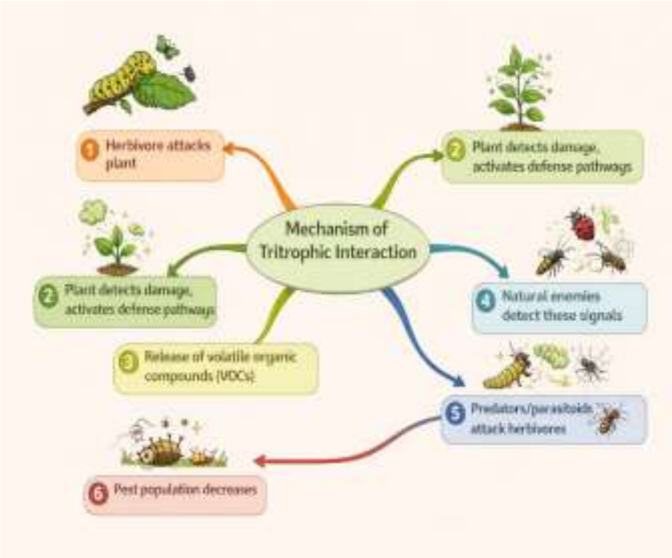
Parasitoids-Lay eggs inside or on host insects, larvae develop by feeding on the host, Eg. *Trichogramma* spp., Braconids

Pathogens- Microorganisms causing diseases in pests. Eg. Fungi, bacteria, viruses

Host/Prey Location Mechanism

Natural enemies locate pests using: Plant-emitted volatiles, herbivore-produced chemicals or by visual and environmental cues

Mechanism of Tritrophic Interaction



Factors Affecting Tritrophic Interactions

Several factors influence these interactions:

Factor Category	Key Influence	Effect on Tritrophic Interaction
Temperature	Affects metabolism	Alters pest-natural enemy balance
Humidity	Influences survival	Affects pathogens and insects
Light	Controls plant activity	Regulates VOC emission
Pesticides	Kills insects	Disrupts natural enemies
Crop	Increases	Enhances

Diversity	biodiversity	biological control
Fertilizers	Affects plant nutrition	Influences pest attraction
Plant Species	Determines VOCs	Controls enemy attraction
Varieties	Genetic resistance	Strengthens interactions

Conclusion

Tritrophic interactions represent a sophisticated ecological relationship that enhances natural pest regulation. Plants, herbivores, and natural enemies are interconnected in a way that promotes biological balance in agroecosystems. Understanding and utilizing these interactions can significantly improve pest management strategies, reduce chemical inputs, and promote sustainable agriculture. Strengthening these natural processes is essential for future food security and environmental conservation.

AGRICULTURE BULLETIN
ISSN: 3049-2289

Economic Viability and Life-Cycle Assessment of Biochar in Carbon Farming Systems

Sonali Khatai
M.Sc. (Agricultural Economics), Division of Agricultural Economics and Agribusiness Management, Sher-e-Kashmir University of Agricultural Sciences and Technology of Jammu, Jammu, India

1.Introduction

Biochar, a stable, carbon-rich material produced via pyrolysis of biomass under oxygen-limited conditions, has emerged as a multifunctional amendment in carbon farming systems. Its application enhances soil fertility, improves crop productivity, and sequesters atmospheric carbon dioxide, contributing to climate change mitigation and sustainable agriculture. Evaluating biochar's role within carbon farming requires a comprehensive understanding of its economic feasibility and environmental sustainability, particularly through cost-benefit analyses and life-cycle assessment (LCA). This paper presents an integrated review of biochar production, application, and long-term impacts, synthesizing agronomic benefits with economic and environmental metrics. The objective is to inform stakeholders, including farmers, policymakers, and researchers, on optimizing biochar deployment to maximize both economic returns and environmental outcomes in diverse agricultural contexts.

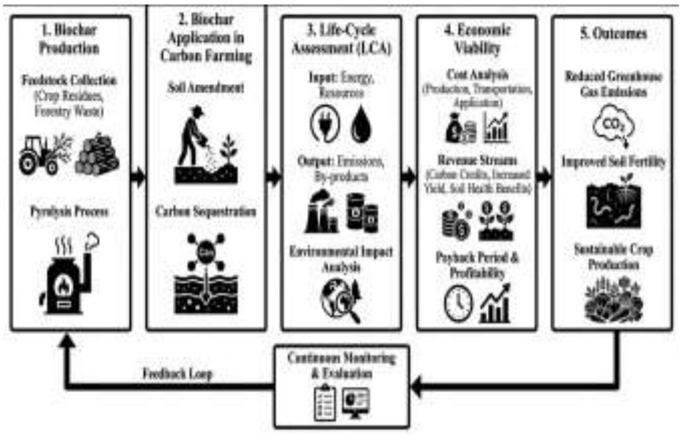


Figure 1: Economic Viability and Life-Cycle Assessment of Biochar

2. Overview of Biochar and Carbon Farming Systems

2.1 Biochar Production and Physicochemical Properties

Biochar production involves thermochemical conversion of organic feedstocks—such as agricultural residues, forestry by-products, and organic wastes—through pyrolysis at temperatures typically ranging from 300°C to 700°C under limited oxygen. The pyrolysis conditions critically influence biochar's physicochemical properties, including surface area, porosity, pH, nutrient content, cation exchange capacity (CEC), and aromatic carbon content. These properties govern biochar's interaction with soil, affecting water retention, nutrient availability, microbial habitat, and carbon stability. Characterization protocols assessing these parameters are essential to ensure consistent quality and predict agronomic performance and carbon sequestration potential.

2.2 Carbon Farming Systems and Biochar Integration

Carbon farming encompasses agricultural and land management practices designed to increase soil organic carbon stocks and reduce greenhouse gas emissions while maintaining or enhancing productivity. Biochar application is a cornerstone strategy within carbon farming, offering a recalcitrant carbon pool resistant to microbial decomposition, thereby stabilizing soil carbon and mitigating atmospheric CO2 levels. Integration methods include direct soil incorporation, co-application with organic or mineral fertilizers, and incorporation into agroforestry, conservation agriculture, or integrated crop-livestock systems. Biochar's multifunctionality supports soil health restoration, nutrient cycling optimization, enhanced water use efficiency, and improved resilience to abiotic stresses such as drought and salinity.

3. Economic Viability of Biochar in Carbon Farming

3.1 Cost Analysis

3.1.1 Feedstock Acquisition and Logistics

Feedstock procurement represents a significant portion of biochar production costs and varies widely depending on biomass availability, type, and regional factors. Agricultural residues such as crop straw or husks may be low-cost or even incur negative costs due to disposal fees, whereas dedicated energy crops or forestry residues may involve higher acquisition and transportation expenses. Efficient logistics, including feedstock densification (pelletization or briquetting) and optimized transport routes, are crucial to minimize costs and environmental impacts. Regional feedstock seasonality and competing uses (e.g., animal feed, bioenergy) also influence availability and pricing.

3.1.2 Pyrolysis Production Costs

Capital expenditures (CAPEX) include the procurement and installation of pyrolysis reactors, emission control systems, and auxiliary equipment. Operational expenditures (OPEX) encompass labor, energy inputs, maintenance, feedstock preprocessing, and consumables. Production scale significantly affects unit costs; larger pyrolysis facilities benefit from economies of scale, reducing per-ton biochar production costs due to improved process efficiencies and fixed cost amortization. Technological innovations, such as continuous pyrolysis reactors and energy recovery systems, further enhance cost-effectiveness.

3.1.3 Transportation and Field Application

Biochar's low bulk density and high volume-to-mass ratio pose logistical challenges in transportation and field application. Transportation costs can be substantial, especially for remote farms or large-scale applications. Field application expenses include spreading equipment, labor, and potential soil incorporation. Technologies such as pelletization or densification improve transport efficiency and facilitate uniform application, reducing costs and enhancing agronomic effectiveness.

3.1.4 Monitoring, Verification, and Certification

Participation in carbon markets or sustainability certification programs requires rigorous monitoring and verification of biochar application rates and associated soil carbon sequestration. These activities incur costs related to soil sampling, laboratory analyses, data management, and third-party auditing. Emerging digital tools and remote sensing technologies offer potential for cost reductions in monitoring but require initial investments and technical capacity.

3.2 Revenue Streams and Economic Benefits

3.2.1 Agronomic Yield Improvements

Biochar amendments improve soil physical and chemical properties, enhancing nutrient retention, water holding capacity, and microbial activity. These improvements translate into increased crop yields and product quality. Yield responses vary with soil type, climate, crop species, and biochar characteristics but can significantly augment farm revenues and offset input costs. Enhanced resilience to drought and disease further contributes to economic stability.

3.2.2 Carbon Credit Monetization

Biochar application qualifies for carbon offset credits under various voluntary and compliance carbon markets, contingent on demonstrating carbon permanence, additionality, and accurate accounting. Carbon credit revenues depend on market prices, certification protocols, and project scale. These financial incentives can substantially improve

ISSN: 3049-2289

biochar project economics, incentivizing adoption and scaling.

3.2.3 Ancillary Benefits

Additional economic advantages include reduced fertilizer and irrigation requirements due to improved nutrient and moisture retention, enhanced soil resilience reducing crop losses, and potential revenues from biochar co-products such as bio-oil and syngas generated during pyrolysis. These co-products may be utilized for energy generation, further offsetting production costs.

3.3 Economic Modeling and Case Studies

Economic viability assessments employ methodologies such as partial budgeting, net present value (NPV), internal rate of return (IRR), payback period, and cost-benefit ratio analyses. Case studies across diverse agroecological zones reveal variability in profitability influenced by feedstock availability, production scale, crop response, and carbon market dynamics. Sensitivity analyses identify key parameters driving economic outcomes, including biochar yield, application rates, carbon pricing, and yield gains, guiding strategic decision-making and risk management.

Economic Viability of Biochar in Carbon Farming

4. Life-Cycle Assessment (LCA) of Biochar in Carbon Farming

4.1 LCA Framework and Scope

Life-cycle assessment systematically evaluates the environmental impacts associated with biochar production and application from feedstock acquisition through pyrolysis, transportation, soil incorporation, and long-term soil carbon dynamics. System boundaries vary but typically include cradle-to-farm gate or cradle-to-grave perspectives. Functional units are often expressed per hectare of amended land or per tonne of biochar produced and applied, facilitating comparability.

4.2 Inventory Analysis

Comprehensive inventory accounts include energy inputs for feedstock collection, preprocessing, and pyrolysis; emissions of greenhouse gases (CO2, CH4, N2O) during production and soil application; transportation distances and modes; biochar yield and stability; and avoided emissions from fossil fuel displacement or waste management alternatives. Data quality and representativeness critically affect LCA reliability.

4.3 Impact Assessment Categories

Key environmental impact categories assessed include:

1. **Global Warming Potential (GWP):** Net greenhouse gas emissions or sequestration over a specified time horizon, commonly 100 years.
2. **Energy Demand:** Total fossil fuel and renewable energy inputs across the biochar life cycle.
3. **Acidification and Eutrophication Potentials:** Emissions contributing to soil and water acidification and nutrient enrichment.
4. **Water Use and Ecotoxicity:** Impacts on freshwater resources and toxicity risks to soil and aquatic biota.
5. **Land Use and Biodiversity:** Effects of feedstock sourcing and land management on ecosystems.

ISSN: 3049-2289

4.4 Biochar Stability and Carbon Sequestration Potential

Biochar's long-term carbon sequestration efficacy depends on its chemical stability, often represented by the proportion of aromatic carbon resistant to microbial degradation. Stability assessments integrate laboratory incubation studies, isotopic tracing, and field trials to estimate mean residence times ranging from decades to centuries. Accurate stability modeling informs GWP calculations, carbon credit eligibility, and policy frameworks.

4.5 Co-Product Allocation and System Interactions

Pyrolysis produces co-products such as bio-oil and syngas, which may be utilized for energy generation or chemical feedstocks. Allocation of environmental burdens among biochar and co-products significantly influences LCA outcomes. Furthermore, avoided emissions from fossil fuel substitution or waste reduction must be incorporated to capture net environmental benefits comprehensively.

Table 1: Life Cycle Assessment (LCA) of Biochar in Carbon Farming Systems

Life Cycle Stage	Inputs	Outputs/Emissions	Environmental Impact	Improvement with Biochar
Feedstock Collection	Crop residues, biomass	Transport emissions	Moderate	Waste utilization
Pyrolysis Process	Energy, biomass	CO_2, syngas, bio-oil	Energy-intensive	Energy recovery possible
Biochar Application	Labor, machinery	Minimal emissions	Low	Soil carbon storage
Crop Production	Fertilizers, irrigation	N_2O, CH_4 emissions	High	Reduced emissions

5. Integration of Economic and Environmental Assessments

5.1 Cost-Effectiveness Metrics

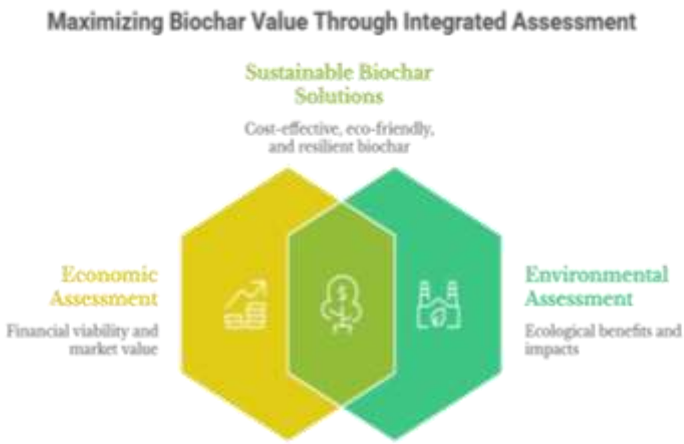
Integrating economic and LCA data enables calculation of the cost per tonne of CO2-equivalent sequestered, a critical metric for comparing biochar to alternative mitigation strategies. This cost-effectiveness analysis informs policy development, investment decisions, and carbon market participation.

5.2 Trade-Off Analysis

Evaluating trade-offs between economic returns, environmental benefits, and potential negative impacts (e.g., energy use, pollutant emissions) facilitates optimization of biochar production scale, feedstock selection, and application rates. Multi-criteria decision analysis (MCDA) frameworks support balanced assessments, incorporating stakeholder preferences and sustainability goals.

5.3 Sensitivity and Uncertainty Analysis

Robust assessments incorporate sensitivity analyses to explore the influence of key variables such as feedstock availability, pyrolysis efficiency, carbon market fluctuations, and soil response variability. Uncertainty analyses quantify confidence levels, guiding risk management and adaptive strategies.



ISSN: 3049-2289

6. Challenges and Opportunities

6.1 Technical and Economic Barriers

High initial capital investments, logistical complexities in feedstock collection and biochar transport, variability in biochar quality, and lack of standardized metrics impede widespread adoption. Addressing these barriers requires technological innovation, supply chain development, and quality assurance protocols.

6.2 Policy and Market Support

Supportive policies—including subsidies, carbon pricing mechanisms, and certification standards—are essential to foster biochar market development. Harmonization of regulatory frameworks and transparent carbon accounting protocols enhance market confidence and investment security.

6.3 Research and Innovation Priorities

Advancements in pyrolysis technology, development of biochar formulations tailored to specific soil types and crops, and integration of agronomic, economic, and environmental modeling are critical. Innovations in monitoring technologies and digital tools can reduce costs and improve verification.

6.4 Social and Environmental Co-Benefits

Beyond carbon sequestration, biochar contributes to soil restoration, water conservation, biodiversity enhancement, and rural economic development. These co-benefits offer pathways for integrated sustainability strategies and community engagement.

7. Regional Case Studies and Perspectives

7.1 Developed Regions

In North America and Europe, large-scale biochar production facilities integrate with waste management systems and precision agriculture practices. Robust policy frameworks and carbon markets support commercialization, with demonstrated agronomic benefits and environmental gains.

7.2 Developing Regions

Smallholder adoption emphasizes decentralized, low-cost pyrolysis units utilizing locally available biomass. Focus areas include soil fertility improvement, climate resilience, and livelihood enhancement. Challenges include limited access to technology, finance, and markets.

7.3 Comparative Insights

Regional variability in feedstock availability, policy environments, agroecological conditions, and socio-economic factors influences biochar's economic and environmental outcomes. Context-specific strategies are necessary to optimize benefits and adoption.

8. Future Directions and Recommendations

8.1 Scaling and Commercialization Strategies

Development of modular, scalable pyrolysis units, diversification of feedstock sources, and establishment of value chains are critical for expanding biochar production. Public-private partnerships and innovation hubs can accelerate technology diffusion.

8.2 Standardization and Certification

International biochar quality standards, carbon credit certification protocols, and transparent reporting frameworks will enhance market acceptance and stakeholder trust.

8.3 Integrated Modeling Approaches

Coupling economic models with dynamic soil carbon, crop growth, and environmental impact simulations improves decision support and policy formulation.

8.4 Stakeholder Engagement

Involving farmers, industry, policymakers, researchers, and communities fosters knowledge exchange, capacity building, and adoption, ensuring that biochar deployment aligns with local needs and sustainability objectives.

ISSN: 3049-2289

9. Conclusion

Biochar represents a promising intervention for carbon sequestration and soil health enhancement within carbon farming systems. Its economic viability depends on feedstock logistics, production efficiency, market mechanisms, and agronomic benefits. Life-cycle assessments substantiate biochar's potential to deliver net environmental gains, contingent upon rigorous system boundary definitions and co-product accounting. Integrating economic and environmental analyses enables informed policy and investment decisions. Addressing technical, economic, and regulatory challenges through innovation and collaboration is imperative to unlock biochar's full potential as a sustainable solution for climate-smart agriculture.

References

Sahoo, K., Upadhyay, A., Runge, T., Bergman, R., Puettmann, M., & Bilek, E. (2021). Life-cycle assessment and techno-economic analysis of biochar produced from forest residues using portable systems. *The International Journal of Life Cycle Assessment*, *26*(1), 189-213.

Roberts, K. G., Gloy, B. A., Joseph, S., Scott, N. R., & Lehmann, J. (2010). Life cycle assessment of biochar systems: estimating the energetic, economic, and climate change potential. *Environmental science & technology*, *44*(2), 827-833.

Carvalho, J., Nascimento, L., Soares, M., Valério, N., Ribeiro, A., Faria, L., ... & Vilarinho, C. (2022). Life cycle assessment (LCA) of biochar production from a circular economy perspective. *Processes*, *10*(12), 2684.

Homagain, K., Shahi, C., Luckai, N., & Sharma, M. (2016). Life cycle cost and economic assessment of biochar-based bioenergy production and biochar land application in Northwestern Ontario, Canada. *Forest ecosystems*, *3*(1), 21.

Shaheen, J., Fseha, Y. H., & Sizirici, B. (2022). Performance, life cycle assessment, and economic comparison between date palm waste biochar and activated carbon derived from woody biomass. *Heliyon*, *8*(12).

James, A., Sánchez, A., Prens, J., & Yuan, W. (2022). Biochar from agricultural residues for soil conditioning: Technological status and life cycle assessment. *Current Opinion in Environmental Science & Health*, *25*, 100314.

ISSN: 3049-2289

Impact of Organic and Integrated Nutrient Management on Growth, Yield, and Quality of Horticultural Crops

Ashutosh Dwivedi and Mansi Khadipure
Ph.D. Scholar, Department of Horticulture (Fruit Science),
Jawaharlal Nehru Krishi Vishwa Vidyalaya, Jabalpur, Madhya Pradesh, India
M.Sc., Department of Horticulture (Vegetable Science),
Jawaharlal Nehru Krishi Vishwa Vidyalaya, Jabalpur, Madhya Pradesh, India

1.Introduction

Horticultural crops, encompassing fruits, vegetables, flowers, and ornamental plants, play a vital role in global food security, human nutrition, and economic development. Sustaining their productivity while minimizing ecological impact is a critical challenge in modern agriculture. Historically, the "Green Revolution" championed the intensive use of synthetic fertilizers, leading to significant yield increases. However, the long-term consequences of this approach—including soil degradation, nutrient runoff, greenhouse gas emissions, and concerns over pesticide residues—have become increasingly evident (Tilman et al., 2002).

In response, sustainable agricultural practices, particularly in nutrient management, have gained prominence. Organic nutrient management (ONM) and integrated nutrient management (INM) represent two distinct yet complementary philosophies aimed at achieving productive and environmentally sound horticultural systems. ONM emphasizes a holistic approach, relying on natural processes and materials to build soil health and provide nutrients. INM, recognizing the potential limitations of an exclusively organic approach in high-demand systems, seeks to judiciously combine the benefits of organic, inorganic, and biological inputs.

This article aims to provide a comprehensive overview of the current understanding of ONM and INM systems, focusing on their specific impacts on the growth, yield, and quality parameters of diverse horticultural crops.

2. Organic Nutrient Management (ONM)

ONM is founded on principles that promote ecological balance, biodiversity, and soil health. It strictly prohibits the use of synthetic fertilizers, pesticides, and genetically modified organisms. Nutrient provision in ONM systems relies on:

a. **Farmyard Manure (FYM):** Decomposed animal excreta mixed with bedding material, a rich source of macro- and micronutrients, and organic matter.

b. **Compost:** Decomposed organic materials (plant residues, food scraps) through controlled aerobic processes, improving soil structure and nutrient availability.

c. **Green Manures:** Crops grown specifically to be incorporated into the soil, enhancing organic matter content and nitrogen fixation (e.g., legumes).

d. **Vermicompost:** Compost produced by earthworms, known for its high nutrient availability and beneficial microbial populations.

e. **Biofertilizers:** Microbial inoculants (e.g., *Rhizobium*, Azotobacter, phosphate-solubilizing bacteria) that enhance nutrient availability and uptake.

f. **Crop Residues:** Leftover plant material after harvest, returned to the soil to recycle nutrients and build organic matter.

2.1. Impact of ONM on Growth and Yield

ONM typically leads to gradual improvements in soil fertility and structure, which in turn support healthy plant growth. While initial yields in ONM systems might be lower than those under conventional management, long-term studies often show comparable or even superior yields as soil health improves.

Table 1 General Trends in Growth and Yield Parameters under ONM vs. Conventional Systems

Parameter	ONM (Short-Term)	ONM (Long-Term)	Conventional Fertilization	Notes
Plant Height	Moderate	Good	Excellent	Gradual improvement with soil health
Leaf Area Index (LAI)	Moderate	Good	Excellent	Reflects overall plant vigor
Root Biomass	Excellent	Excellent	Good	Enhanced by improved soil structure
Total Biomass	Moderate	Good	Excellent	Initial slower growth
Marketable Yield	Slightly Lower	Comparable/Good	Excellent	Yield gap narrows over time

For vegetables like tomatoes, ONM has been shown to improve root development and nutrient cycling, leading to sustained yields (Mäder et al., 2002). In fruit crops, improved soil moisture retention and microbial activity under ONM can enhance fruit set and development.

2.2. Impact of ONM on Quality

The most significant advantages of ONM often manifest in the quality attributes of horticultural produce.

a. **Nutritional Content:** Studies frequently report higher concentrations of vitamins (e.g., Vitamin C), antioxidants (e.g., phenolic compounds, carotenoids), and essential minerals in organically grown fruits and vegetables compared to conventionally grown counterparts (Worthington, 2001; Baranski et al., 2014). This is attributed to slower nutrient release, which encourages plants to invest more in secondary metabolites for defence and adaptation.

b. **Sensory Properties:** Consumers often perceive organically grown produce as having superior flavour, aroma, and texture. This can be linked to a balanced nutrient supply and reduced nitrate accumulation.

c. **Shelf Life:** While not consistently superior, some studies suggest that organically grown produce may exhibit better post-harvest quality and extended shelf life due to higher total soluble solids (TSS) and less susceptibility to physiological disorders.

d. **Reduced Nitrates:** Organically managed soils tend to have lower levels of available nitrogen, leading to lower nitrate accumulation in leafy vegetables, which is a significant human health concern.

3. Integrated Nutrient Management (INM)

INM is a flexible and site-specific approach that aims to maximize the benefits of organic, inorganic, and biological nutrient sources while minimizing their respective drawbacks. The core principle is to maintain or enhance soil fertility and plant nutrient supply to achieve optimal productivity and quality in an environmentally benign manner.

Key components of INM include:

a. **Soil Testing:** Regular analysis to determine nutrient status and guide fertilizer recommendations.

b. **Organic Amendments:** Use of FYM, compost, green manures, and crop residues as in ONM, but often in conjunction with synthetic inputs.

c. **Synthetic Fertilizers:** Judicious application of chemical fertilizers (e.g., NPK) based on crop demand, soil test results, and critical growth stages, often in reduced doses.

d. **Biofertilizers:** Microbial inoculants to enhance nutrient availability and uptake.

e. **Crop Rotation:** Inclusion of legumes to fix atmospheric nitrogen and break pest/disease cycles.

f. **Precision Nutrient Application:** Techniques like fertigation and foliar feeding to apply nutrients directly to the plant or root zone, minimizing waste.

3.1. Impact of INM on Growth and Yield

INM often outperforms both conventional chemical fertilization (in terms of sustainability) and pure ONM (in terms of immediate yield potential), especially during the transition phase to organic farming.

a. **Optimized Nutrient Availability:** By combining quick-release synthetic fertilizers with slow-release organic sources, INM ensures a steady supply of nutrients throughout the crop's growth cycle, leading to vigorous growth and higher yields.

b. **Improved Soil Health:** The inclusion of organic amendments under INM enhances soil physical, chemical, and biological properties, improving water holding capacity, nutrient retention, and microbial activity, which directly translates to better plant growth.

c. **Reduced Nutrient Losses:** Synergistic effects between organic and inorganic sources can reduce leaching and volatilization of nutrients, particularly nitrogen, making more available for plant uptake.

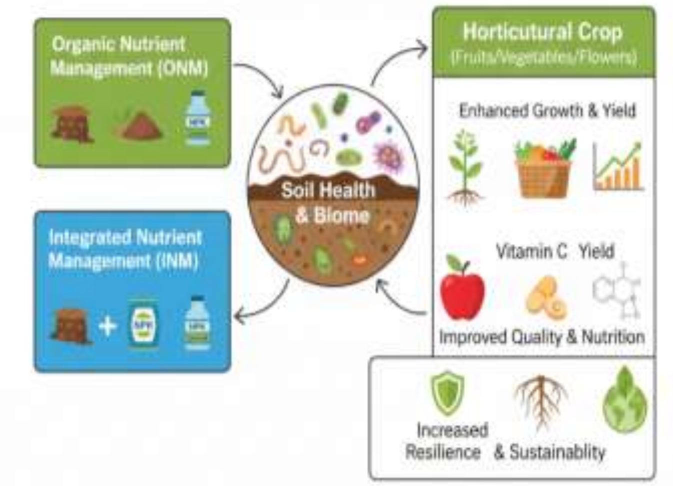
Research on various horticultural crops, such as potatoes, onions, and various fruit trees, has consistently shown that INM treatments result in significantly higher yields compared to ONM alone and often comparable yields to conventional systems but with improved soil health (Sharma & Arora, 2017; Adhikary et al., 2018).

3.2. Impact of INM on Quality

INM offers a balanced approach to quality, aiming to achieve both high yield and desirable quality attributes.

a. **Nutritional Content:** INM systems can maintain or even enhance the nutritional quality of produce, often leading to higher levels of vitamins, minerals, and antioxidants compared to conventional systems. The balanced nutrient supply avoids excessive nitrogen accumulation while supporting the synthesis of health-promoting compounds.

b. **Sensory Properties:** Similar to ONM, the integration of organic inputs in INM can contribute to improved flavour, aroma, and texture.



c. **Reduced Environmental Contaminants:** By reducing reliance on synthetic inputs and promoting efficient nutrient use, INM minimizes the risk of nitrate accumulation in produce and environmental pollution.

d. **Shelf Life:** Improved plant health and balanced nutrition under INM can lead to produce with better structural integrity and disease resistance, potentially enhancing shelf life.

e. Figure 1 Holistic impacts of nutrient management on horticultural crops

Comparative Analysis and Discussion

Both ONM and INM offer viable pathways for sustainable horticultural production, each with distinct advantages and challenges.

Table 2 Comparative Analysis of ONM and INM in Horticultural Crop Production

Feature	Organic Nutrient Management (ONM)	Integrated Nutrient Management (INM)
Philosophy	Holistic, ecological, prohibits synthetics.	Pragmatic, combines the best of organic, inorganic, and biological.
Primary Nutrient Source	Organic manures, composts, biofertilizers, green manures.	A mix of organic, chemical, and biofertilizers.
Soil Health	Excellent, long-term improvement, high microbial diversity.	Very good, progressive improvement, balanced microbial activity.
Short-Term Yield	Often lower, especially during the transition phase.	Generally good, often comparable to conventional, stable.
Long-Term Yield	Good, can be comparable to conventional as soil health improves.	Excellent, often superior to ONM and sustainable conventional.
Nutritional Quality	Often superior (vitamins, antioxidants, minerals).	Good to excellent, balanced nutritional profile.
Environmental Impact	Very low, promotes biodiversity, and reduces pollution.	Low, reduced pollution compared to conventional, improved nutrient use

ISSN: 3049-2289

		efficiency.
Input Cost	Variable, often lower for purchased inputs, higher for labor.	Variable, potentially optimized by reducing synthetic fertilizer use.
Complexity	Requires deep understanding of ecological processes.	Requires careful planning, soil testing, and balanced application.
Certification	Strict standards for organic certification.	No specific certification, focuses on sustainable practices.

The choice between ONM and INM depends on various factors including the specific crop, agro-climatic conditions, farmer's objectives, market demand, and available resources. For high-value horticultural crops where premium prices can be obtained for certified organic produce, ONM might be the preferred choice. However, for many commercial growers seeking to optimize yields while moving towards sustainability, INM offers a pragmatic and highly effective solution.

4. Challenges and Future Directions

Despite the clear benefits, both ONM and INM face challenges:

a. **Nutrient Availability and Synchronization (ONM):** The slow release of nutrients from organic sources can sometimes lead to nutrient deficiencies, especially for crops with high nutrient demands or during critical growth stages. Synchronizing nutrient release with crop uptake remains a significant challenge.

b. **Bulkiness of Organic Manures:** Transportation and application of large quantities of organic manures can be labour-intensive and costly.

c. **Knowledge Gap:** Effective implementation of both systems requires a comprehensive understanding of soil biology, nutrient cycling, and crop-specific nutrient requirements, which may be lacking among some growers.

d. **Transition Period (ONM):** The initial years of converting to organic farming can result in yield reductions, posing an economic risk for farmers.

e. **Optimization of INM:** Precisely determining the optimal combination of organic and inorganic inputs for specific crops and soil types requires ongoing research and adaptive management.

Future research should focus on:

- **Enhanced Biofertilizer Efficacy:** Developing more effective and robust biofertilizer formulations suitable for diverse soil and climatic conditions.
- **Precision Organic Nutrient Management:** Technologies for sensing nutrient availability from organic sources and developing decision support systems for their application.
- **Long-Term Comparative Studies:** More extensive long-term research across different horticultural crops and regions to robustly compare the economic and environmental sustainability of ONM and INM.
- **Impact on Crop Resilience:** Investigating the role of ONM and INM in enhancing crop resistance to pests, diseases, and climate change stressors.
- **Life Cycle Assessment (LCA):** Comprehensive LCAs to quantify the environmental footprint of

both systems, including greenhouse gas emissions, water use, and energy consumption.

5. Conclusion

The analysis confirms that both Organic Nutrient Management (ONM) and Integrated Nutrient Management (INM) represent viable, critical paradigms for transitioning horticultural production toward sustainability. They fundamentally address the limitations of conventional systems, which prioritize short-term yield at the expense of long-term soil health and environmental integrity.

5.1. Synthesis of Findings

- **ONM** is the ecological champion. It fosters superior soil quality, microbial diversity, and ecosystem services, and consistently delivers produce with enhanced nutritional and quality attributes (higher antioxidants, lower nitrates). Economically, while facing initial yield penalties during transition, the long-term viability is often sustained by premium prices in niche markets and reduced variable input costs.
- **INM** is the pragmatic bridge. By combining the quick efficacy of judiciously applied mineral fertilizers with the soil-building benefits of organic inputs, INM typically achieves high, stable yields that often match or surpass conventional systems, all while significantly improving Nutrient Use Efficiency (NUE) and mitigating environmental pollution. It offers a crucial, flexible entry point for commercial growers committed to sustainable practices.

5.2. The Imperative for Integrated Adoption

The future of horticulture is not about choosing one system over the other, but recognizing the appropriate role for each:

- **INM** is essential for global food security by maintaining high productivity on existing land while simultaneously restoring soil capital.
- **ONM** sets the gold standard for environmental protection and food quality, driving innovation in soil biology and low-input systems.

5.3. Policy and Research Mandates

To accelerate the adoption of these sustainable systems, supportive policy and concentrated research are mandatory:

1. **Incentivizing the Transition:** Governments must implement robust policy mechanisms (e.g., direct subsidies, tax breaks, carbon sequestration payments) to offset the financial risk and productivity losses during the multi-year conversion phase, particularly for smallholder farmers.
2. **Infrastructure Development:** Investment is needed in regional infrastructure for producing and standardizing high-quality organic inputs (compost, biofertilizers) to reduce the bulkiness challenge of ONM and ensure a consistent supply for INM.
3. **Precision Agriculture Integration:** Research must continue to push the boundaries of precision sensing and modeling to remove the primary barrier of ONM—the lack of nutrient synchronization. Developing reliable, affordable tools for real-time soil and plant nutrient status will make organic and integrated systems more predictable and efficient.
4. **Economic Viability:** Promoting shorter supply chains and transparent certification standards (for organic produce) is essential to ensure that the premium prices paid by consumers are adequately captured by the growers, reinforcing the long-term economic viability of both ONM and INM.

References

Adhikary, A., Sarkar, B. P., Mondal, R., & Adhikary, S. (2018). Integrated nutrient management in potato (*Solanum tuberosum* L.). *Journal of Crop and Weed*, *14*(3), 227-230.

ISSN: 3049-2289

Baranski, M., Srednicka-Tober, D., Volakakis, N., Seal, R., Sanderson, C. H., Stewart, G. B., ... & Leifert, C. (2014). Higher antioxidant and lower cadmium concentrations in organically grown crops: a systematic literature review and meta-analyses. *British Journal of Nutrition*, *112*(5), 794-811.

Mäder, P., Fliessbach, A., Dubois, D., Gunst, L., Fried, P., & Niggli, U. (2002). Soil fertility and biodiversity in organic farming. *Science*, *296*(5573), 1694-1697.

Sharma, S., & Arora, S. (2017). Integrated nutrient management (INM) for sustainable vegetable production: A review. *International Journal of Current Microbiology and Applied Sciences*, *6*(4), 1461-1471.

Tilman, D., Cassman, K. G., Matson, P. A., Naylor, R., & Polasky, S. (2002). Agricultural sustainability and intensive production practices. *Nature*, *418*(6898), 671-677.

Worthington, V. (2001). Nutritional quality of organic versus conventional fruits, vegetables, and grains. *Journal of Complementary and Alternative Medicine*, *7*(2), 161-173.

AGRICULTURE BULLETIN
ISSN: 3049-2289

GIS-Based Soil Fertility Mapping for Improved Crop Production Management

Monu Kumar Yadav, Ashish Vishnawat, and Punita Dhankar
M.Sc. (Agriculture), Department of Soil Science and Agricultural Chemistry, Agriculture University Jodhpur, Jodhpur, Rajasthan, India
Ph.D. Research Scholar, Department of Soil Science and Agricultural Chemistry, Maharana Pratap University of Agriculture and Technology, Udaipur, Rajasthan, India
Ph.D. Research Scholar, Department of Soil Science and Agricultural Chemistry, Swami Keshwanand Rajasthan Agricultural University, Bikaner, Rajasthan, India

Introduction

Geographic Information Systems (GIS) play a pivotal role in modern agriculture by enabling precise soil fertility mapping, which addresses the inherent spatial variability of soil properties across agricultural fields. This variability significantly affects nutrient availability and crop productivity, making uniform fertilizer applications inefficient and environmentally detrimental. GIS-based soil fertility mapping integrates systematic soil sampling, laboratory analyses, and spatial interpolation techniques to produce detailed, high-resolution nutrient distribution maps. These maps facilitate site-specific nutrient management, allowing farmers to optimize fertilizer application rates according to the unique conditions of different field zones.

Beyond soil nutrient data, GIS platforms incorporate additional layers such as remote sensing imagery, topography, historical yield records, and climatic factors, providing a comprehensive context for decision-making. This multidimensional approach enhances nutrient use efficiency, reduces input costs, improves crop yields and quality, and mitigates environmental risks like nutrient runoff and leaching.

Advances in GPS technology, data processing, and user-friendly GIS interfaces have broadened access to these tools. When combined with precision agriculture technologies such as variable rate application equipment and decision support systems, GIS enables dynamic, real-time nutrient management. Overall, GIS-based soil fertility mapping represents a transformative shift towards sustainable, precision agriculture, balancing agronomic productivity with environmental stewardship and supporting long-term agricultural resilience.

Figure 1: GIS-Based Soil Fertility Mapping for Improved Crop Production Management

Importance of Soil Fertility in Crop Production

Soil fertility is a fundamental driver of crop growth, yield, and quality, as it governs the availability of essential macro- (nitrogen, phosphorus, potassium) and micronutrients (zinc, iron, manganese, copper, boron, molybdenum, chlorine). However, soil properties are inherently heterogeneous due to variations in parent material, topography, organic matter content, and management history. This spatial variability results in uneven nutrient availability within fields. Conventional uniform fertilizer applications often fail to address this variability, leading to nutrient overuse in some areas and deficiencies in others, resulting in economic inefficiencies and environmental degradation including nutrient leaching, runoff, and soil degradation. GIS-based soil fertility mapping addresses these challenges by providing spatially resolved nutrient information, enabling site-specific nutrient management and improved agronomic outcomes.

Components of GIS-Based Soil Fertility Mapping

Soil Sampling and Data Collection

Accurate soil fertility mapping begins with a well-designed soil sampling strategy that captures spatial variability within the field. Sampling methods include grid, stratified random, and zone-based approaches. The choice depends on field size, heterogeneity, and management objectives. Sampling density is critical; higher densities improve map resolution but increase costs. Each soil sample location is precisely georeferenced using GPS devices to ensure spatial accuracy.

Laboratory Analysis

Soil samples undergo comprehensive chemical and physical analyses to quantify nutrient concentrations (N, P, K, micronutrients), pH, electrical conductivity, organic carbon content, cation exchange capacity (CEC), and texture. These parameters collectively define soil fertility status and constraints, providing the basis for nutrient management decisions.

Georeferencing and Data Management

Sample data are linked to GPS coordinates and integrated into GIS databases. Rigorous data quality control, validation, and metadata documentation are essential to ensure the reliability and traceability of soil fertility data.

Spatial Interpolation and Fertility Mapping

Since soil samples provide point data, spatial interpolation techniques estimate soil fertility parameters across unsampled locations, creating continuous surface maps. Common methods include kriging, inverse distance weighting (IDW), and spline interpolation. The choice of method depends on data distribution, spatial autocorrelation, and desired accuracy.

Layering and Thematic Mapping

Individual nutrient maps can be overlaid with other spatial data such as topography, land use, historical yield data, and soil texture to create composite thematic maps. These layered maps provide comprehensive insights into nutrient deficiencies, toxicities, and management zones.

Soil Sampling Strategies and Best Practices

1. **Grid Sampling:** Systematic sampling at uniform intervals provides even spatial coverage, suitable for relatively homogeneous fields.
2. **Stratified Random Sampling:** Divides the field into strata based on known variability factors (soil type, topography) and samples randomly within each stratum to capture heterogeneity.

3. **Zone Sampling:** Targets distinct management zones identified by remote sensing, yield data, or prior knowledge to optimize sampling efforts.
4. **Composite Sampling:** Combines multiple subsamples from a small area to reduce analysis costs while maintaining representativeness.
5. **Sampling Depth Considerations:** Surface (0–15 cm) and subsurface (15–30 cm) sampling capture nutrient stratification relevant to crop rooting zones.

Laboratory Analysis and Soil Fertility Indicators

1. **Macro- and Micronutrient Quantification:** Measurement of essential nutrients including nitrogen (N), phosphorus (P), potassium (K), zinc (Zn), iron (Fe), manganese (Mn), copper (Cu), boron (B), molybdenum (Mo), and chlorine (Cl).
2. **Soil pH and Electrical Conductivity (EC):** pH influences nutrient solubility and availability; EC indicates salinity, affecting plant health.
3. **Organic Matter Content:** Critical for nutrient retention, soil structure, and microbial activity.
4. **Cation Exchange Capacity (CEC):** Reflects soil's capacity to hold and exchange nutrient cations.
5. **Soil Texture and Structure:** Influence water retention, aeration, and nutrient dynamics.

Georeferencing and Data Management in GIS

1. **Accurate GPS Use:** Employing high-precision GPS units ensures exact location tagging of samples, critical for spatial accuracy.
2. **Data Quality Control:** Includes consistency checks, outlier detection, and validation of laboratory results.
3. **Database Design:** Structuring spatial and attribute data for efficient retrieval, analysis, and integration within GIS platforms.
4. **Metadata Documentation:** Recording sampling dates, methods, depth, and laboratory procedures to maintain data integrity and reproducibility.

Spatial Interpolation Techniques for Fertility Mapping

1. **Kriging:** A geostatistical method that models spatial autocorrelation to provide unbiased predictions with error estimation, ideal for datasets with spatial structure.
2. **Inverse Distance Weighting (IDW):** Estimates values based on proximity to sampled points, weighting nearer points more heavily; simpler but less statistically robust.
3. **Spline Interpolation:** Fits smooth surfaces through data points, useful for gently varying datasets.
4. **Method Selection:** Depends on data characteristics, spatial variability, and required accuracy; kriging generally preferred for precision mapping.

Thematic and Composite Soil Fertility Mapping

1. **Individual Nutrient Maps:** Visualize spatial distribution of key nutrients, highlighting zones of deficiency or excess.
2. **Soil Fertility Indices:** Composite indices integrating multiple parameters simplify interpretation and guide management decisions.
3. **Risk and Deficiency Zones:** Identification of critical areas enables targeted interventions.
4. **Temporal Mapping:** Monitoring fertility changes over seasons or years supports adaptive management and soil health tracking.

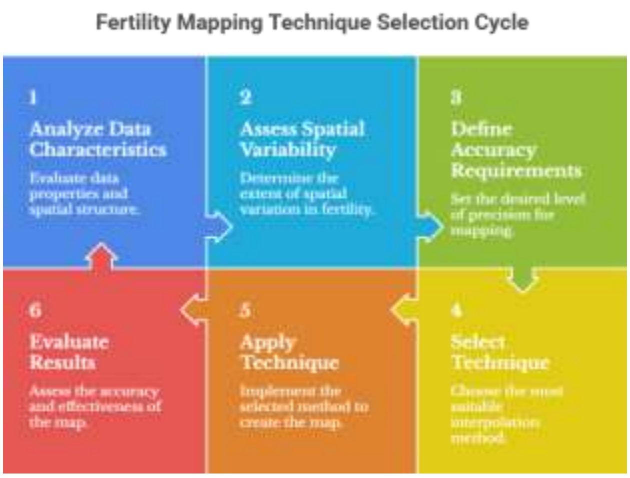
ISSN: 3049-2289

Integration of Remote Sensing with GIS Soil Fertility Mapping

1. **Vegetation Indices (NDVI, EVI):** Derived from satellite or drone imagery, these indices correlate with crop vigor and nutrient status, providing indirect fertility indicators.
2. **Soil Moisture and Temperature Mapping:** Influences nutrient availability and uptake dynamics.
3. **High-Resolution Imagery:** Enhances spatial detail and accuracy of fertility assessments.
4. **Unmanned Aerial Vehicles (UAVs):** Provide flexible, timely, and cost-effective data acquisition for dynamic monitoring.

Decision Support Systems (DSS) and Variable Rate Fertilization

1. **Prescription Map Generation:** Converts fertility maps into actionable fertilizer application plans tailored to site-specific nutrient requirements.
2. **Integration with Farm Machinery:** GPS-guided fertilizer applicators implement site-specific nutrient delivery, enhancing precision.
3. **Economic Optimization Models:** Balance input costs and yield benefits to maximize profitability.
4. **User-Friendly Interfaces:** Design of intuitive DSS platforms facilitates farmer adoption and informed decision-making.



Benefits of GIS-Based Soil Fertility Mapping for Crop Production Management

1. **Precision Nutrient Management:** Tailors fertilizer application rates to spatial variability, improving nutrient use efficiency.
2. **Increased Crop Yields and Quality:** Corrects nutrient imbalances precisely, enhancing productivity and product quality.
3. **Cost Savings:** Reduces fertilizer over-application and labor costs.
4. **Environmental Protection:** Minimizes nutrient runoff, leaching, and associated water pollution.
5. **Improved Soil Health Monitoring:** Enables tracking of fertility trends, supporting sustainable management.
6. **Enhanced Decision-Making:** Provides actionable insights for agronomic planning and resource allocation.

Precision Nutrient Management Techniques

1. **Site-Specific Fertilizer Application:** Matches nutrient supply spatially with crop demand.
2. **Split Applications:** Timing fertilization to coincide with peak nutrient uptake periods to reduce losses.
3. **Use of Organic Amendments:** Targeted application of compost or manure to deficient zones enhances soil fertility.
4. **Integration with Crop Rotation Plans:** Supports nutrient cycling and long-term soil health.

Cost-Benefit Analysis of GIS-Based Fertility Management

1. **Input Cost Savings:** Reduction in fertilizer use through precise application.
2. **Yield Increases:** Quantifiable improvements in crop productivity.

ISSN: 3049-2289

3. **Return on Investment (ROI):** Demonstrates economic feasibility for farms of various sizes.
4. **Environmental Cost Reduction:** Valuation of ecosystem services preserved by minimizing pollution.

Environmental Impacts and Sustainability

1. **Reduction of Nutrient Runoff:** Protects aquatic ecosystems from eutrophication.
2. **Soil Erosion Control:** Maintains soil structure and fertility.
3. **Carbon Sequestration Potential:** Improved soil management enhances carbon storage.
4. **Biodiversity Conservation:** Supports beneficial soil microorganisms and fauna.

Integration with Emerging Technologies

1. **Internet of Things (IoT) and Soil Sensors:** Provide real-time measurements of soil moisture, temperature, and nutrient status, complementing static GIS maps.
2. **Artificial Intelligence and Machine Learning:** Enable predictive modeling and adaptive nutrient management based on integrated datasets.
3. **Big Data Analytics:** Combine multi-source information for comprehensive farm management.
4. **Mobile and Cloud-Based Platforms:** Enhance accessibility, scalability, and real-time decision support.

Table 1: Integration of GIS with Advanced Technologies

Technology	Role in Soil Fertility Mapping	Advantage
Remote Sensing	Large-scale soil variability detection	Real-time monitoring
GPS	Accurate geo-referencing	Precision sampling
Machine Learning	Predictive modeling of nutrients	High accuracy
Drones	Field-level data collection	Rapid assessment

Challenges and Limitations in GIS-Based Soil Fertility Mapping

1. **Sampling Intensity vs. Cost Trade-offs:** Balancing map resolution with resource availability.
2. **Data Uncertainty and Error Propagation:** Ensuring accuracy in interpolation and analysis.
3. **Technical Skill Requirements:** Necessity for trained personnel in soil science and GIS.
4. **Infrastructure and Technology Access:** Availability of GPS devices, software, and compatible machinery.
5. **Farmer Adoption Barriers and Training Needs:** Overcoming knowledge gaps and resistance.
6. **Temporal Variability:** Soil fertility changes over time, requiring periodic updates for accuracy.

Policy, Extension Services, and Capacity Building

1. **Role of Government and Institutions:** Providing infrastructure, subsidies, and regulatory frameworks to support precision agriculture adoption.
2. **Extension Programs:** Training farmers and agronomists in GIS applications and precision nutrient management.

3. **Public-Private Partnerships:** Facilitating technology dissemination and support services.
4. **Standardization of Protocols:** Ensuring data quality, interoperability, and best practices.

Future Directions and Innovations

1. **Real-Time Adaptive Fertilization Systems:** Dynamic nutrient management based on sensor feedback integrated with GIS.
2. **Multi-Scale Fertility Mapping:** From field to regional and landscape scales for comprehensive management.
3. **Integration with Crop Growth Models:** Predicting nutrient demand dynamically to optimize fertilization.
4. **Sustainability and Environmental Footprint Metrics:** Incorporating ecological impact assessments into nutrient management decisions.
5. **Farmer-Centric Decision Tools and Mobile Applications:** Enhancing usability, accessibility, and adoption of GIS-based tools.

Conclusion

GIS-based soil fertility mapping is an essential tool for modern agriculture, enabling precise nutrient management that enhances crop productivity, reduces environmental impacts, and improves economic returns. By capturing spatial variability in soil properties and integrating with complementary technologies such as remote sensing, IoT sensors, and decision support systems, GIS facilitates sustainable intensification and climate resilience. Addressing challenges related to sampling, data quality, technical capacity, and farmer engagement is crucial for widespread adoption. Continued innovation and user-focused tool development will ensure GIS-based soil fertility mapping remains integral to sustainable agricultural systems.

References

LANKI, D. A. (2024). Geographic Information System (GIS) application in soil fertility management: a review. *Journal of Global Agriculture and Ecology*.

AbdelRahman, M. A., Hegab, R. H., & Yossif, T. M. (2021). Soil fertility assessment for optimal agricultural use using remote sensing and GIS technologies. *Applied Geomatics*, *13*(4), 605-618.

Raza, I., Zubair, M., Zaib, M., Khalil, M. H., Haidar, A., Sikandar, A., ... & Ashfaq, M. A. (2023). Precision nutrient application techniques to improve soil fertility and crop yield: A review with future prospect. *International Research Journal of Educational and Tecnology*, *5*.

Singh, V. K., Govil, V., Singh, S. K., Dwivedi, B. S., Meena, M. C., Gupta, V. K., ... & Gangwar, B. (2012). Precision nutrient management strategies using GIS-based mapping in Western Uttar Pradesh. *Better Crops-South Asia*, *6*(1), 15-18.

Mathenge, M., Sonneveld, B. G., & Broerse, J. E. (2022). Application of GIS in agriculture in promoting evidence-informed decision making for improving agriculture sustainability: A systematic review. *Sustainability*, *14*(16), 9974.

El Baroudy, A. A. (2016). Mapping and evaluating land suitability using a GIS-based model. *Catena*, *140*, 96-104.

AGRICULTURE BULLETIN
ISSN: 3049-2289

Nano-Encapsulated Organic Micronutrients for Improved Nutrient Use Efficiency in Sustainable Farming

Sandhya Dabral
M.Sc. Scholar, Department of Soil Science, Govind Ballabh Pant University of Agriculture and Technology, Pantnagar

1.Introduction

Sustainable agriculture aims to meet current food demands while preserving environmental health and resource availability for future generations. Nutrient management is a cornerstone of sustainable farming, directly impacting crop productivity, soil health, and environmental quality. Micronutrients such as zinc (Zn), iron (Fe), manganese (Mn), copper (Cu), boron (B), and molybdenum (Mo), though required in trace amounts, are essential for plant physiological processes, enzyme functions, and stress tolerance. Deficiencies in micronutrients can severely limit crop yields and nutritional quality.

Traditional micronutrient fertilization practices often suffer from low nutrient use efficiency (NUE) due to factors such as fixation in soil, leaching, volatilization, and poor plant availability. These inefficiencies not only increase input costs but also pose environmental risks through contamination of water bodies and soil degradation. Moreover, the over-application of micronutrients can lead to toxicity issues affecting plants and soil microbial communities.

Nanotechnology offers innovative solutions to overcome these challenges by enabling the design of nano-encapsulated organic micronutrients. Nano-encapsulation involves enclosing micronutrient particles within organic carriers at the nanoscale, enhancing their stability, bioavailability, controlled release, and targeted delivery. This technology improves nutrient uptake efficiency, reduces losses, and minimizes environmental impacts, aligning with the principles of sustainable farming. This presents a comprehensive analysis of nano-encapsulated organic micronutrients, covering their synthesis, physicochemical properties, mechanisms of nutrient release and uptake, agronomic benefits, environmental implications, challenges, and future prospects. Emphasis is placed on how this emerging technology can transform micronutrient management, enhance crop productivity, and contribute to sustainable intensification of agriculture.

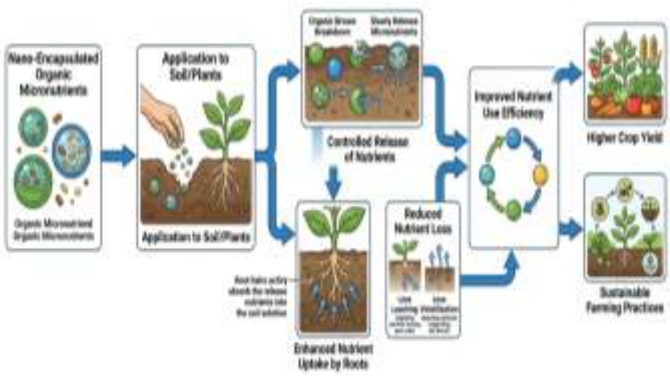


Figure 1: Nano-Encapsulated Organic Micronutrients for Improved Nutrient Use Efficiency in Sustainable Farming

2. Role and Importance of Micronutrients in Plant Growth

Micronutrients such as zinc (Zn), iron (Fe), manganese (Mn), copper (Cu), boron (B), molybdenum (Mo), and cobalt (Co) are indispensable for various biochemical and physiological processes in plants. They act as cofactors for enzymes, participate in electron transport chains, and regulate growth hormones. Deficiencies in micronutrients manifest as stunted growth, chlorosis, necrosis, and reduced yield quality. Organic micronutrients, including chelated forms and bioactive compounds, improve solubility and mobility in soils, facilitating better uptake by plants. Understanding the soil-plant micronutrient dynamics is crucial for designing effective nano-encapsulated formulations that provide sustained nutrient availability and reduce environmental losses.

Table 1: Characteristics and Functional Advantages of Nano-Encapsulated Organic Micronutrients

Parameter	Nano-Encapsulated Micronutrients	Conventional Micronutrients	Mechanism/Feature	Impact (%)
Particle Size	Nano-scale (1–100 nm)	Micro/large particles	Higher surface area	Enhanced reactivity
Release Pattern	Controlled and slow release	Rapid release	Encapsulation matrix	20–50% reduced losses
Nutrient Use Efficiency (NUE)	High	Low to moderate	Targeted delivery	25–60% improvement
Leaching Losses	Minimal	High	Strong adsorption and slow release	20–40% reduction
Bioavailability	High	Limited	Increased root absorption	15–35% increase
Environmental Impact	Eco-friendly	Potential pollution	Reduced runoff and toxicity	Sustainable use
Dosage Requirement	Lower	Higher	Efficient nutrient utilization	15–30% reduction
Stability	High (protected form)	Low (prone to degradation)	Encapsulation protection	Improved shelf life

3. Nano-Encapsulation Technology: Principles and Methods

Nano-encapsulation is an advanced delivery system in which micronutrients are enclosed within nanometer-scale carriers (1–100 nm), enabling protection from environmental degradation and facilitating controlled, site-specific nutrient release. This technology operates on the principle of enhancing nutrient stability, minimizing losses through leaching, volatilization, and fixation, and improving plant uptake efficiency through increased surface area and reactivity.

At the nano-scale, physicochemical interactions such as adsorption, diffusion, and electrostatic binding become highly efficient, allowing precise control over nutrient release kinetics. Additionally, nano-encapsulation enables synchronization between nutrient availability and crop demand, thereby significantly improving nutrient use efficiency (NUE). These systems also act as smart delivery platforms, responding dynamically to environmental stimuli such as pH, temperature, moisture, and enzymatic activity.

3.1 Types of Nano-Carriers (Expanded)

a) Polymeric Nanoparticles Polymeric nanocarriers, derived from biodegradable and biocompatible materials such as chitosan, alginate, and cellulose derivatives, are widely used due to their environmental safety and tunable properties. These carriers can encapsulate micronutrients through ionic interactions or physical entrapment. Their release behavior is governed by swelling, degradation, or diffusion processes, which are influenced by soil moisture and microbial activity. Chitosan-based nanoparticles, for instance, not only deliver nutrients but also exhibit antimicrobial properties, enhancing plant health.

b) Liposomes Liposomes are spherical vesicles composed of phospholipid bilayers capable of encapsulating both hydrophilic and lipophilic micronutrients. Their structural similarity to biological membranes allows efficient fusion with plant cell membranes, facilitating rapid nutrient absorption. Liposomes are particularly effective in foliar applications, where they enhance nutrient penetration through the cuticle and improve systemic transport within the plant.

c) Nanogels Nanogels are three-dimensional hydrophilic polymer networks capable of absorbing large amounts of water while maintaining structural integrity. These carriers are highly responsive to environmental stimuli such as pH, temperature, and moisture, enabling smart and controlled nutrient release. Their high loading capacity and biocompatibility make them suitable for sustained nutrient delivery in varying soil conditions.

d) Inorganic Nanoparticles Inorganic carriers such as silica, clay minerals, and metal oxides provide structural stability and controlled diffusion of nutrients. Mesoporous silica nanoparticles, for example, offer high surface area and pore volume, allowing efficient nutrient loading and gradual release. Clay-based nanocomposites improve nutrient retention and reduce leaching losses, particularly in sandy soils. However, their long-term environmental impact requires careful evaluation.

3.2 Nano-Encapsulation Techniques

a) Emulsion Polymerization This technique involves the formation of nanoscale droplets stabilized by surfactants, within which micronutrients are encapsulated during polymerization. It enables uniform particle size distribution and high encapsulation efficiency, making it suitable for large-scale production.

b) Coacervation Coacervation is a phase separation process in which a polymer-rich coating forms around nutrient particles. This method allows precise control over coating thickness and release rate. Complex coacervation using natural polymers enhances biodegradability and compatibility with organic farming systems.

c) Spray Drying Spray drying converts liquid nutrient formulations into dry, stable powders through rapid atomization and solvent evaporation. This method is cost-effective, scalable, and widely used for commercial fertilizer production. It also improves storage stability and ease of handling.

d) Sol–Gel Process The sol–gel technique involves the formation of a three-dimensional network (gel) from a colloidal solution (sol), encapsulating micronutrients within inorganic or hybrid matrices. This process provides excellent control over particle structure, porosity, and release characteristics, making it suitable for advanced nano-fertilizer formulations.

4. Organic Micronutrients Suitable for Nano-Encapsulation (Expanded)

Organic micronutrients, derived from natural and biodegradable sources, are particularly suitable for nano-encapsulation due to their compatibility with sustainable agriculture. These compounds not only

ISSN: 3049-2289

supply essential nutrients but also improve soil biological activity and plant physiological processes.

a) Zinc and Iron Chelates Organic chelates such as Zn-EDTA and Fe-EDDHA enhance micronutrient solubility and prevent precipitation in alkaline soils. Nano-encapsulation further improves their stability, reduces fixation, and ensures gradual release, leading to higher uptake efficiency and improved crop productivity.

b) Humic and Fulvic Acids Humic substances act as natural chelators, enhancing nutrient availability and stimulating plant growth. When nano-encapsulated, they improve nutrient retention, promote microbial activity, and enhance root development. Fulvic acid, due to its lower molecular weight, facilitates rapid nutrient transport within plant tissues.

c) Plant-Derived Extracts Plant extracts rich in micronutrients, amino acids, and bioactive compounds serve as eco-friendly nutrient sources. Nano-encapsulation enhances their stability and delivery efficiency, enabling improved plant metabolism, stress tolerance, and growth regulation.

5. Mechanisms of Nutrient Release and Plant Uptake

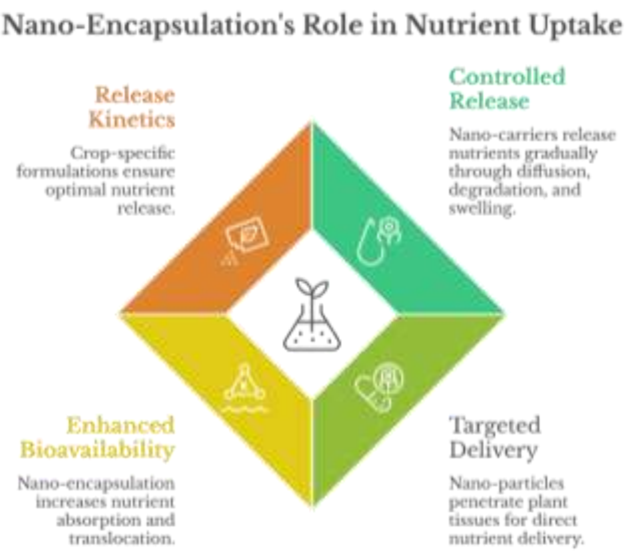
Nano-encapsulation enables precise regulation of nutrient release and uptake, ensuring efficient synchronization with plant physiological needs.

a) Controlled Release Mechanisms Nano-carriers release nutrients gradually through mechanisms such as diffusion, degradation, and swelling. Environmental triggers like soil moisture, pH variations, and microbial activity influence these processes. This controlled release minimizes nutrient losses and ensures sustained availability over time.

b) Targeted Delivery and Uptake Due to their nanoscale size, encapsulated particles can penetrate plant root epidermis, cortical cells, and even leaf cuticles more efficiently than conventional fertilizers. This enhances direct nutrient delivery to active metabolic sites, improving uptake efficiency.

c) Enhanced Bioavailability and Translocation Nano-encapsulated nutrients exhibit increased surface reactivity and interaction with plant cell membranes, facilitating efficient absorption. Once inside the plant system, nutrients are translocated through xylem and phloem to various tissues, supporting metabolic activities such as photosynthesis, enzyme activation, and stress response.

d) Release Kinetics and Crop Specificity The rate and pattern of nutrient release depend on factors such as nano-carrier composition, environmental conditions, soil properties, and crop type. Therefore, designing crop-specific and site-specific formulations is essential for maximizing the effectiveness of nano-encapsulated micronutrients.



6. Agronomic Benefits of Nano-Encapsulated Organic Micronutrients

a) **Enhanced Nutrient Use Efficiency:** By reducing nutrient losses through leaching, volatilization, and fixation, nano-encapsulation optimizes fertilizer inputs and improves crop yields.

b) **Reduced Environmental Impact:** Controlled release minimizes nutrient runoff and contamination of soil and water bodies.

c) **Improved Crop Quality:** Balanced and sustained micronutrient supply supports physiological functions, enhancing nutritional content, disease resistance, and market value.

d) **Soil Health Preservation:** Encourages beneficial soil microbial populations and reduces accumulation of toxic residues from excess fertilizers.

e) **Compatibility with Organic Farming:** Use of biodegradable nano-carriers and organic nutrient sources aligns with organic certification standards and sustainable agriculture principles.

7. Environmental and Safety Considerations

While nano-encapsulation reduces nutrient losses and environmental contamination, the environmental fate and potential toxicity of nanoparticles require thorough assessment. Biodegradable carriers such as chitosan and alginate mitigate risks of nanoparticle accumulation. However, comprehensive life cycle assessments, including production, application, degradation, and disposal phases, are essential to ensure sustainable deployment. Studies must evaluate nanoparticle persistence, bioaccumulation, and impacts on non-target soil organisms and ecosystems.

8. Production Challenges and Economic Considerations

a) **Cost of Production:** The complex processes involved in nano-encapsulation, including material synthesis and quality control, can increase costs compared to conventional fertilizers, potentially limiting adoption by smallholder farmers.

b) **Scalability:** Transitioning from laboratory or pilot-scale production to commercial-scale manufacturing requires optimization of processes to maintain quality and reduce costs.

c) **Regulatory Framework:** Currently, there is a lack of comprehensive regulations and safety standards governing the use of nanomaterials in agriculture, creating uncertainty for manufacturers and users.

d) **Farmer Awareness and Training:** Effective dissemination of knowledge about the benefits, application methods, and safety of nano-fertilizers is crucial to foster acceptance and correct usage.

9. Future Prospects and Research Directions

a) **Smart Nano-Carriers:** Development of stimuli-responsive nano-carriers capable of releasing nutrients in response to specific environmental or plant signals (e.g., moisture, pH, root exudates) for precision nutrient management.

b) **Multi-Nutrient Formulations:** Encapsulation of micronutrient blends and macronutrients to address complex soil deficiencies and reduce the number of fertilizer applications.

c) **Integration with Precision Agriculture:** Combining nano-fertilizers with sensor technologies and data analytics to optimize spatial and temporal nutrient application, minimizing waste and maximizing efficiency.

d) **Regulatory and Safety Frameworks:** Establishment of standardized guidelines for the production, application, and environmental monitoring of nano-fertilizers to ensure safe and sustainable use.

e) **Farmer Engagement and Capacity Building:** Development of extension services, training programs, and demonstration projects to promote awareness, acceptance, and correct application practices among farmers.

10. Conclusion

Nano-encapsulation of organic micronutrients presents a transformative strategy to enhance nutrient use efficiency and sustainability in agriculture. By protecting micronutrients, enabling controlled release, and facilitating targeted delivery, this technology addresses many limitations of conventional fertilization methods. Despite challenges related to production costs, regulatory uncertainties, and environmental safety, ongoing research and technological innovations are paving the way for widespread adoption. Integrating nano-encapsulated organic micronutrients with sustainable farming practices promises to improve crop productivity, reduce environmental footprints, and contribute significantly to global food security.

References

Singh, S., Kumar, M., Panotra, N., Shashidhar, K. S., Yadav, V., & Mohanty, L. K. Precision Nutrition: Harnessing Nano-fertilizers and Smart Inputs for a Paradigm Shift in Nutrient Use Efficiency (NUE).

Kalra, T., Tomar, P. C., & Arora, K. (2020). Micronutrient encapsulation using nanotechnology: nanofertilizers. *Plant Arch*, *20*(2), 1748-1753.

Mishra, P., Meena, R. K., & Joshi, R. (2025). Nanofertilizers and Nanopesticides: Unlocking Potential for Safe and Sustainable Agriculture with a Focus on Organic Farming. In *Nanofertilizers for Sustainable Agriculture: Assessing Impacts on Health, Environment, and Economy* (pp. 101-125). Cham: Springer Nature Switzerland.

Singh, N., Liu, Y. H., Das, D., Shameem, N., Parray, J. A., Li, W. J., ... & Ghazi, R. M. (2025). Nano-enabled strategies for plant stress management and sustainable crop production: A review. *Agronomy Journal*, *117*(6), e70230.

Jayaraj, G., Balasubramaniam, M., & Raju, K. (2025). Nanoencapsulation of Agricultural Inputs. In *Nanotechnology Applications in Modern Agriculture* (pp. 51-79). Cham: Springer Nature Switzerland.

Ray, A., Das, P., Chunduri, R., Kumar, D., Dulta, K., Kaushal, A., ... & Sharma, A. (2025). Nanocomposite-based agricultural delivery systems: a sustainable approach to enhanced crop productivity and soil health. *Journal of Nanoparticle Research*, *27*(4), 110.

AGRICULTURE BULLETIN
ISSN: 3049-2289

Pyramiding Multiple Resistance Genes for Durable Immunity

Udit Prakash and Nakka Amulya
Ph.D. Scholar, Department of Genetics and Plant Breeding, Agriculture University Jodhpur, Jodhpur, Rajasthan, India
Ph.D. Scholar, Department of Genetics and Plant Breeding, Agriculture University Jodhpur, Jodhpur, Rajasthan, India

1.Introduction

Plant diseases caused by a wide array of pathogens including fungi, bacteria, viruses, and nematodes pose significant threats to global food security by reducing crop yields and quality. Host plant resistance, conferred by specific resistance (R) genes, is a cornerstone of sustainable disease management due to its cost-effectiveness and environmental safety compared to chemical control methods. However, resistance governed by single R genes often lacks durability, as pathogen populations rapidly evolve to overcome such monogenic resistance, leading to resistance breakdown and recurrent epidemics.

To address this challenge, pyramiding multiple resistance genes combining two or more R genes into a single cultivar has emerged as a robust strategy to achieve durable and broad-spectrum immunity. This approach enhances resistance effectiveness by creating a complex genetic barrier that reduces the probability of pathogen adaptation. The stacking of multiple genes can confer resistance against diverse pathogen races or species and prolong the lifespan of resistance traits under field conditions.

This comprehensive review delves into the molecular basis of plant immunity, the rationale and benefits of gene pyramiding, breeding and biotechnological strategies for gene stacking, molecular interactions among pyramided genes, challenges faced in pyramiding, and future prospects. It integrates advances in genomics, molecular breeding, and genome editing that have revolutionized the efficiency and precision of pyramiding, highlighting case studies of successful applications. The review also discusses the integration of gene pyramiding within integrated disease management frameworks to achieve sustainable crop protection.

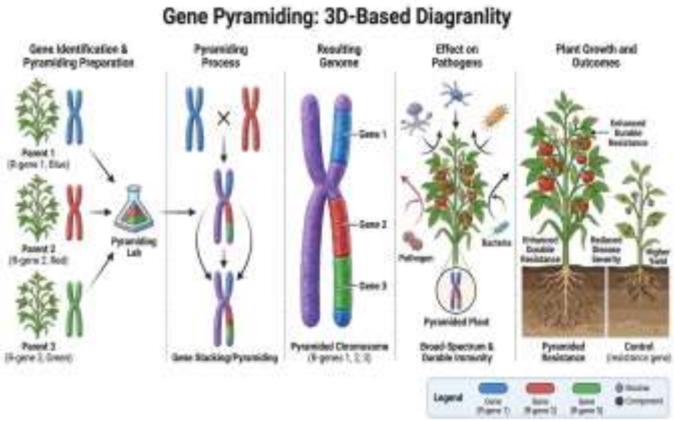


Figure 1: Mechanism of Gene Pyramiding for Enhanced Durable Immunity in Plants

2. Fundamentals of Plant Immunity and Resistance Genes

2.1 Plant Immune System Overview

Plants possess a sophisticated innate immune system consisting of two primary layers:

1. **Pattern-Triggered Immunity (PTI):** This basal defense mechanism is activated upon recognition of conserved pathogen-associated molecular patterns (PAMPs) by pattern recognition receptors (PRRs) located on the plant cell surface. PTI induces a broad-spectrum defense response that includes reinforcement of cell walls, production of reactive oxygen species, and expression of defense-related genes. Although PTI provides general resistance, many pathogens secrete effectors that suppress PTI, facilitating infection.

2. **Effector-Triggered Immunity (ETI):** ETI represents a more robust and often race-specific defense activated when intracellular resistance (R) proteins detect specific pathogen effectors. These R proteins, frequently encoded by R genes, typically belong to the nucleotide-binding site leucine-rich repeat (NBS-LRR) family. ETI often triggers a hypersensitive response (HR), characterized by localized programmed cell death that restricts pathogen spread. ETI is generally stronger and more effective than PTI but can be overcome by pathogen evolution.

The interplay between PTI and ETI forms a dynamic defense network that determines the outcome of plant-pathogen interactions. Understanding this system is fundamental to exploiting resistance genes for durable immunity.

2.2 Classification and Function of Resistance Genes

Resistance genes encode proteins responsible for recognizing pathogen effectors and initiating defense signaling. Major classes include:

a) **Nucleotide-binding site leucine-rich repeat (NBS-LRR) proteins:** The largest and most studied class, these intracellular receptors detect specific pathogen effectors either directly or indirectly through guard or decoy mechanisms. They comprise a central nucleotide-binding domain and a C-terminal leucine-rich repeat domain responsible for effector recognition.

b) **Receptor-like kinases (RLKs) and receptor-like proteins (RLPs):** These membrane-bound receptors participate in PAMP recognition and some R gene-mediated resistance, triggering PTI or ETI responses.

c) **Other classes:** Include proteins involved in signaling cascades, transcriptional regulation, and enzymatic defense responses.

R gene-mediated resistance is often highly specific but vulnerable to pathogen adaptation. Consequently, strategies that combine multiple R genes are required to enhance resistance durability.

Table 1: Types of Resistance Genes Used in Gene Pyramiding

Gene Type	Example Genes	Mechanism of Resistance	Target Pathogen	Advantage
Major (R) Genes	Xa21 (rice), Lr34 (wheat)	Race-specific recognition	Bacteria, fungi	Strong resistance
Minor (QTL) Genes	qBR genes (rice)	Quantitative resistance	Broad-spectrum pathogens	Durable resistance
Adult Plant Resistance (APR)	Lr34, Yr18	Stage-specific resistance	Rust diseases	Long-lasting effect
Broad-Spectrum Genes	Pi genes (rice blast)	Multi-pathogen defense	Multiple pathogens	Wide protection
Transgenic Resistance	Bt gene	Toxin production	Insects	High effectiveness

3. Concept and Rationale of Gene Pyramiding

3.1 Definition and Objectives

Gene pyramiding involves the stacking of multiple R genes conferring resistance to one or more pathogens or pathogen races into a single plant genotype. The key objectives are:

a) **Broadening Resistance Spectrum:** Combining genes that confer resistance to different pathogen races or species to achieve wide-ranging protection.

b) **Increasing Resistance Durability:** Creating a genetic barrier that makes it difficult for pathogens to simultaneously overcome multiple resistance mechanisms.

c) **Enhancing Resistance Stability:** Ensuring consistent resistance expression across diverse environments and pathogen pressures.

3.2 Theoretical Basis for Durability Enhancement

Durable resistance is achieved because pathogens must accumulate multiple mutations or virulence factors to overcome all pyramided R genes simultaneously. The likelihood of simultaneous adaptation is significantly lower than adaptation to a single gene, thereby prolonging the effective lifespan of resistance. Additionally, pyramiding can provide complementary or synergistic defense mechanisms, further impeding pathogen evolution.

4. Strategies and Approaches for Pyramiding Resistance Genes

4.1 Conventional Breeding Approaches

Traditional pyramiding involves crossing donor lines carrying individual R genes and selecting progeny with the desired gene combinations. This process includes:

a) **Hybridization and Backcrossing:** Controlled crosses followed by backcrossing to elite cultivars to recover agronomic traits.

b) **Phenotypic Selection:** Screening progenies under controlled inoculation or field disease pressure to identify resistant individuals.

Limitations include long breeding cycles, labor-intensive phenotyping, difficulty in distinguishing individual gene effects, linkage drag of undesirable traits, and complex inheritance patterns.

4.2 Marker-Assisted Selection (MAS)

MAS utilizes molecular markers tightly linked to R genes to enable precise selection without phenotypic screening. Benefits include:

a) Accelerated breeding cycles through early generation selection.

b) Ability to pyramid multiple genes simultaneously.

c) Facilitates stacking of minor-effect quantitative resistance loci.

Challenges include the requirement for well-characterized markers, knowledge of gene positions, and potential recombination between markers and target genes.

4.3 Genomic Selection and High-Throughput Genotyping

Advancements in sequencing technologies have enabled:

a) **High-Density SNP Genotyping:** Screening thousands of markers across the genome to track multiple R genes efficiently.

b) **Genomic Selection (GS):** Using genome-wide marker data to predict breeding values, facilitating selection of individuals with optimal gene combinations even for complex traits.

GS is particularly advantageous for pyramiding quantitative resistance loci or genes with minor effects.

4.4 Genetic Engineering and Genome Editing

a) **Transgenic Approaches:** Introduction of multiple R genes from diverse sources into elite cultivars, bypassing sexual incompatibility and linkage drag.

b) **Genome Editing (CRISPR/Cas9 and others):** Precise insertion or modification of R genes, enabling targeted pyramiding with minimal off-target effects.

These technologies allow rapid, precise pyramiding but face regulatory, biosafety, and public acceptance challenges.

Table 2: Strategies for Gene Pyramiding in Crop Improvement

Strategy	Method	Tools Used	Advantage	Limitation
Conventional Breeding	Crossing & selection	Phenotypic screening	Simple, low-cost	Time-consuming
Marker-Assisted Selection (MAS)	DNA marker tracking	SSR, SNP markers	Accurate gene stacking	Requires markers
Marker-Assisted Backcrossing (MABC)	Backcross + markers	Molecular markers	Rapid recovery of parent traits	Technical expertise
Genomic Selection	Whole-genome prediction	AI/ML models	High efficiency	Expensive
Genetic Engineering	Gene insertion	CRISPR, transgenics	Precise gene stacking	Regulatory issues

5. Molecular Interactions and Epistasis in Gene Pyramiding

5.1 Additive and Synergistic Effects

Pyramided R genes can exert additive effects, where combined resistance equals the sum of individual gene effects, or synergistic effects, where resistance exceeds additive expectations due to enhanced recognition or signaling amplification. Synergism can manifest as increased hypersensitive response intensity, broader pathogen recognition, or prolonged defense activation.

5.2 Negative Interactions and Gene Silencing

a) **Epistasis:** Certain gene combinations may interfere with each other's expression or function, leading to reduced resistance compared to expectations.

b) **Gene Silencing:** Transcriptional or post-transcriptional gene silencing, especially in transgenic pyramids, can suppress expression of one or more R genes, diminishing overall resistance.

Detailed molecular characterization and functional validation are essential to avoid negative interactions and optimize pyramiding outcomes.

ISSN: 3049-2289

6. Case Studies of Successful Gene Pyramiding

6.1 Rice Blast Resistance

Rice blast, caused by *Magnaporthe oryzae*, is a devastating disease worldwide. Pyramiding multiple blast resistance genes such as Pi1, Pi2, Pi9, and Pita has resulted in cultivars exhibiting broad-spectrum and durable resistance. Marker-assisted pyramiding has accelerated development of these cultivars, which show reduced disease incidence across diverse environments.

6.2 Wheat Rust Resistance

Wheat rust diseases, particularly stem rust caused by *Puccinia graminis* f. sp. *tritici*, pose major threats. Pyramiding stem rust resistance genes Sr2, Sr24, Sr25, and Sr26 has enhanced resistance durability, including protection against the virulent Ug99 lineage. These pyramided lines have been deployed successfully in breeding programs worldwide.

6.3 Potato Late Blight Resistance

Late blight, caused by *Phytophthora infestans*, severely affects potato production. Pyramiding R genes from wild *Solanum* species, such as Rpi-blb1, Rpi-blb2, and Rpi-vnt1, has conferred durable resistance, significantly reducing fungicide dependency and yield losses.

7. Challenges and Limitations of Gene Pyramiding

7.1 Pathogen Evolution and Resistance Breakdown

Despite pyramiding, pathogens can still evolve through mutation, recombination, or effector diversification to overcome stacked resistance genes, especially under intense selection pressure. Continuous pathogen monitoring and deployment strategies are necessary to mitigate this risk.

7.2 Genetic Linkage and Breeding Complexity

Linkage drag of undesirable traits linked to R genes complicates breeding. Complex inheritance patterns, such as epistasis and gene interactions, make pyramiding challenging, requiring extensive breeding and molecular tools.

7.3 Phenotyping and Validation

Accurate phenotyping for multiple gene effects and resistance durability across diverse environments remains a bottleneck. Controlled inoculation and field trials are resource-intensive.

7.4 Resource and Technical Constraints

High costs, requirement for molecular markers, genotyping facilities, and skilled personnel limit pyramiding adoption, particularly in developing countries.

8. Integration of Gene Pyramiding with Integrated Disease Management (IDM)

Gene pyramiding should be integrated within holistic IDM frameworks that combine:

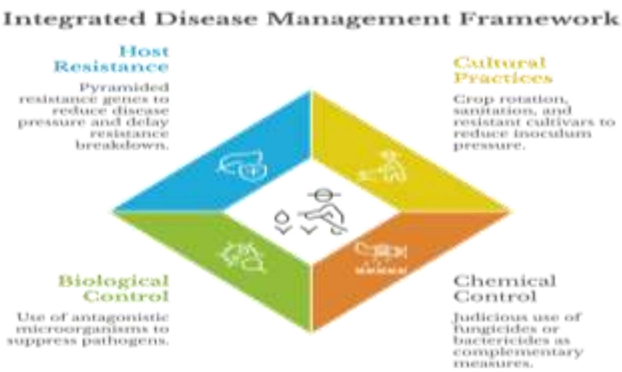
a) **Cultural Practices:** Crop rotation, sanitation, and resistant cultivar deployment to reduce inoculum pressure.

b) **Chemical Control:** Judicious use of fungicides or bactericides as complementary measures.

c) **Biological Control:** Use of antagonistic microorganisms to suppress pathogens.

d) **Host Resistance:** Pyramided resistance genes reduce disease pressure and delay resistance breakdown.

This integrated approach enhances overall disease management efficacy and sustainability.



9. Future Perspectives and Innovations

9.1 Advances in Genomics and Bioinformatics

Whole-genome sequencing, pan-genomics, and transcriptomics facilitate discovery of novel R genes, understanding of resistance mechanisms, and identification of candidate genes for pyramiding.

9.2 Precision Breeding and Synthetic Biology

Synthetic biology enables design of synthetic R gene constructs and multiplex genome editing for customized pyramids with optimized gene combinations and minimal linkage drag.

9.3 Systems Biology and Network Analysis

Modeling complex host-pathogen interactions and signaling networks informs rational gene selection and pyramiding strategies, improving resistance durability.

9.4 Deployment Strategies

Spatial and temporal deployment of pyramided cultivars, including gene rotation and mosaic planting, can manage pathogen populations and delay resistance breakdown.

10. Conclusion

Pyramiding multiple resistance genes is a robust and promising strategy to achieve durable, broad-spectrum immunity against plant pathogens, critical for sustainable crop protection and food security. Advances in molecular breeding, genomics, and biotechnology have enhanced the efficiency and precision of pyramiding. However, challenges remain in understanding gene interactions, pathogen adaptation, and integrating pyramiding into comprehensive disease management systems. Continued research, innovation, and multidisciplinary collaboration are essential to fully harness gene pyramiding's potential for resilient and sustainable agriculture.

References

Mundt, C. C. (2018). Pyramiding for resistance durability: theory and practice. *Phytopathology*, *108*(7), 792-802.

Pilet-Nayel, M. L., Moury, B., Caffier, V., Montarry, J., Kerlan, M. C., Fournet, S., ... & Delourme, R. (2017). Quantitative resistance to plant pathogens in pyramiding strategies for durable crop protection. *Frontiers in plant science*, *8*, 1838.

Fukuoka, S., Saka, N., Mizukami, Y., Koga, H., Yamanouchi, U., Yoshioka, Y., ... & Yano, M. (2015). Gene pyramiding enhances durable blast disease resistance in rice. *Scientific reports*, *5*(1), 7773.

Fuchs, M. (2017). Pyramiding resistance-conferring gene sequences in crops. *Current opinion in virology*, *26*, 36-42.

Ramalingam, J., Raveendra, C., Savitha, P., Vidya, V., Chaithra, T. L., Velprabakaran, S., ... & Vanniarajan, C. (2020). Gene pyramiding for achieving enhanced resistance to bacterial blight, blast, and sheath blight diseases in rice. *Frontiers in plant science*, *11*, 591457.

Amit Kaushik, A. K., Vineet Kaswan, V. K., Sudhir Sharma, S. S., & Rakesh Kumar, R. K. (2016). Gene pyramiding: a novel approach for disease resistance.

Thorat, S., Gangwar, R. K., & Sisodiya, D. (2024). Gene pyramiding an advanced approach for disease management in rice: A review. *Innovations in Agriculture*, *7*, 1-12.

AGRICULTURE BULLETIN
ISSN: 3049-2289

Remote Sensing Techniques for Crop Health Assessment and Precision Nutrient Management

Punita Dhankar, Ashish Vishnawat, and Monu Kumar Yadav
Ph.D. Research Scholar, Department of Soil Science and Agricultural Chemistry, Swami Keshwanand Rajasthan Agricultural University, Bikaner, Rajasthan, India
Ph.D. Research Scholar, Department of Soil Science and Agricultural Chemistry, Maharana Pratap University of Agriculture and Technology, Udaipur, Rajasthan, India
M.Sc. (Agriculture), Department of Soil Science and Agricultural Chemistry, Agriculture University Jodhpur, Jodhpur, Rajasthan, India

Introduction

Remote sensing has become an essential technology in modern agriculture, offering a non-invasive, efficient, and large-scale means to monitor crop health and manage nutrients precisely. By capturing electromagnetic radiation reflected or emitted by crops and soils via satellites, aircraft, drones, or ground sensors, remote sensing provides detailed spatial and temporal information on plant physiological status and environmental conditions. This capability enables early detection of nutrient deficiencies, stress factors, and disease outbreaks before they become visually apparent, allowing timely interventions. Integrating remote sensing data with geographic information systems (GIS) and decision support tools facilitates site-specific nutrient management, optimizing fertilizer application rates to match crop needs and spatial variability within fields. Such precision reduces input costs, enhances nutrient use efficiency, improves crop yields and quality, and minimizes negative environmental impacts like nutrient runoff and greenhouse gas emissions. Advances in sensor technology, data processing, and platform accessibility have expanded the practical applications of remote sensing, making it a cornerstone of sustainable, climate-smart agriculture. This introduction sets the stage for a comprehensive exploration of remote sensing techniques in crop health assessment and precision nutrient management.

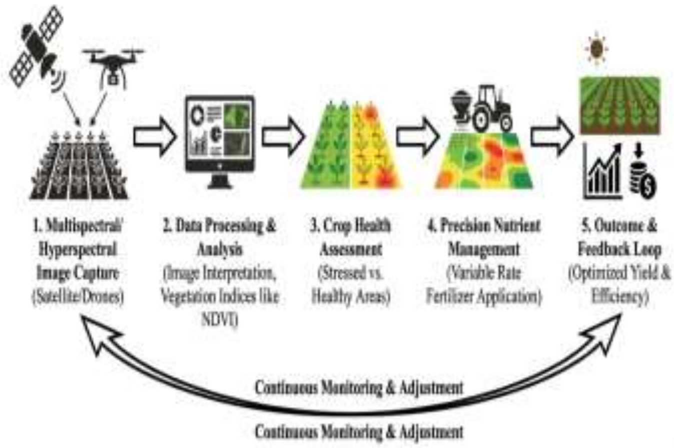


Figure 1: Remote Sensing Techniques for Crop Health Assessment and Precision Nutrient Management

Fundamentals of Remote Sensing in Agriculture

1. **Principles of Remote Sensing**

Remote sensing involves acquiring information about objects or areas without direct contact, typically through the detection of electromagnetic radiation reflected or emitted by vegetation and soil surfaces. The key components include:

1.1. **Electromagnetic Spectrum Utilization:** Remote sensing exploits different spectral regions, notably visible (VIS), near-infrared (NIR), shortwave infrared (SWIR), and thermal infrared (TIR) bands. Each band provides unique insights into crop and soil properties.

1.2. **Spectral Signatures:** Vegetation and soil exhibit characteristic reflectance patterns across spectral

ISSN: 3049-2289

bands, which vary with crop type, health status, and stress conditions, enabling differentiation and assessment.

1.3. **Spatial Resolution:** Defines the smallest discernible object size within an image. High spatial resolution allows detailed field-level monitoring but may reduce temporal frequency.

1.4. **Temporal Resolution:** Refers to the frequency of data acquisition, critical for capturing dynamic crop growth stages and stress events.

1.5. **Radiometric Resolution:** The sensor's sensitivity to detect subtle variations in reflected or emitted radiation, influencing data quality.

2. **Types of Remote Sensing Platforms**

2.1. **Satellite-Based Sensors:** Offer extensive coverage with varying spatial and temporal resolutions. Common platforms include Landsat, Sentinel, MODIS, and commercial satellites providing high-resolution imagery.

2.2. **Aerial Sensors:** Mounted on manned aircraft, these provide flexible deployment options with high spatial resolution, suitable for regional surveys.

2.3. **Unmanned Aerial Vehicles (UAVs)/Drones:** Provide ultra-high spatial and temporal resolution imagery ideal for detailed field-scale assessments and rapid data acquisition.

2.4. **Ground-Based Sensors:** Proximal sensing devices such as spectroradiometers and multispectral cameras capture detailed canopy or leaf-level measurements, complementing aerial and satellite data.

Figure 2: UAV (Drone)-Based Remote Sensing

Remote Sensing Data Types and Their Relevance to Crop Health

1. **Multispectral Imaging**

Multispectral sensors capture reflectance data across several discrete spectral bands, typically including visible and near-infrared wavelengths. These data facilitate the calculation of vegetation indices that serve as proxies for crop vigor, biomass, and nutrient status.

2. **Hyperspectral Imaging**

Hyperspectral sensors acquire data in hundreds of narrow, contiguous spectral bands, allowing detailed analysis of subtle spectral features associated with biochemical and biophysical crop properties. This capability enables precise detection of nutrient deficiencies and disease symptoms.

3. **Thermal Imaging**

Thermal sensors detect emitted infrared radiation, providing canopy temperature measurements indicative of plant water stress, transpiration rates, and indirectly, nutrient status. Elevated canopy temperatures may signal stomatal closure due to nutrient or water stress.

4. **LiDAR (Light Detection and Ranging)**

LiDAR systems emit laser pulses to capture three-dimensional crop structural information, including plant height, canopy density, and

ISSN: 3049-2289

biomass. This data assists in assessing crop vigor and spatial variability.

Vegetation Indices for Crop Health Assessment

Vegetation indices (VIs) are mathematical combinations of spectral bands designed to enhance vegetation signals while minimizing background noise. They provide quantitative measures of chlorophyll content, leaf area index (LAI), photosynthetic activity, and stress levels.

1. **Normalized Difference Vegetation Index (NDVI):** Calculates the contrast between NIR and red reflectance to estimate green biomass and photosynthetic activity, widely used for general crop health monitoring.
2. **Enhanced Vegetation Index (EVI):** Improves upon NDVI by correcting for atmospheric interference and soil background effects, offering better sensitivity in dense vegetation canopies.
3. **Soil-Adjusted Vegetation Index (SAVI):** Incorporates a soil brightness correction factor, useful for assessing vegetation in areas with sparse cover.
4. **Chlorophyll Indices (e.g., CIgreen, CIRE):** Target specific chlorophyll absorption features to assess nutrient status and photosynthetic capacity.
5. **Photochemical Reflectance Index (PRI):** Reflects photosynthetic efficiency and early stress responses by measuring changes in carotenoid pigments.

Table 1: Key Vegetation Indices for Crop Health Assessment

Index	Formula	Key Use	Special Advantage
NDVI	(NIR − Red) / (NIR + Red)	Biomass & crop vigor	Simple, widely used
EVI	2.5 × (NIR − Red) / (NIR + 6Red − 7.5Blue + 1)	Dense vegetation monitoring	Reduces atmospheric & soil effects
SAVI	[(NIR − Red)/(NIR + Red + L)] × (1 + L)	Sparse vegetation	Soil-adjusted accuracy
CI (Green/Red Edge)	(NIR/Green) − 1	Chlorophyll & nutrient status	Sensitive to nitrogen content
PRI	(R531 − R570) / (R531 + R570)	Photosynthetic efficiency	Detects early stress

Remote Sensing for Nutrient Deficiency Detection

1. Spectral Signatures of Nutrient Deficiencies

Nutrient deficiencies induce physiological and biochemical changes in plants, altering pigment concentrations and leaf structure, which affect spectral reflectance patterns. For example, nitrogen deficiency reduces chlorophyll content, leading to increased reflectance in the visible spectrum and decreased NIR reflectance.

2. Vegetation Indices Sensitivity

Indices sensitive to chlorophyll and pigment content, such as NDVI and chlorophyll indices, facilitate early detection of nutrient stress before visual symptoms manifest.

ISSN: 3049-2289

3. **Hyperspectral Analysis**

The detailed spectral resolution of hyperspectral data allows discrimination of specific nutrient deficiencies by identifying subtle shifts in spectral features associated with individual nutrient-related physiological changes.

4. **Thermal Imaging Applications**

Nutrient stress can cause stomatal closure, reducing transpiration and increasing canopy temperature, detectable via thermal sensors, providing indirect evidence of nutrient limitations.

Precision Nutrient Management Using Remote Sensing

1. **Site-Specific Nutrient Application**

Remote sensing data enable mapping of spatial variability in crop nutrient status and soil fertility, guiding variable rate fertilizer applications tailored to field zones. This targeted approach optimizes nutrient use efficiency, reduces input costs, and minimizes environmental pollution.

2. **Nutrient Deficiency Mapping**

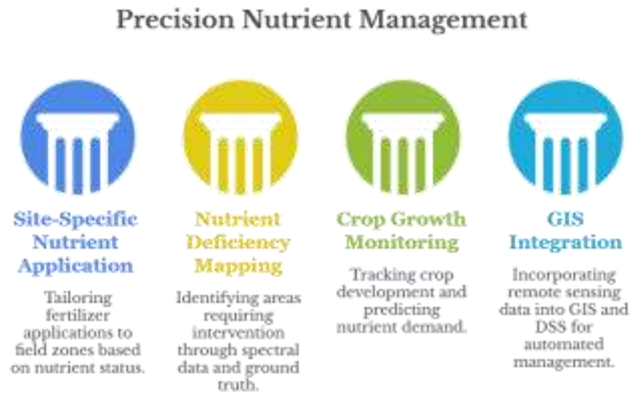
By integrating spectral data with ground truth measurements, nutrient deficiency maps can be generated to pinpoint areas requiring intervention, ensuring precise application of fertilizers or amendments.

3. **Crop Growth Monitoring and Forecasting**

Temporal remote sensing datasets track crop development stages and predict nutrient demand, facilitating timely fertilizer applications synchronized with crop growth cycles.

4. **Integration with GIS and Decision Support Systems**

Remote sensing outputs are incorporated into Geographic Information Systems (GIS) and decision support systems (DSS) to produce prescription maps for variable rate technology (VRT) equipment, enabling automated, site-specific nutrient management.



Remote Sensing Data Processing and Analysis

1. **Preprocessing Procedures**

1.1. **Radiometric Calibration:** Converts raw sensor signals to reflectance values, standardizing data for comparison.

1.2. **Atmospheric Correction:** Removes atmospheric distortions such as scattering and absorption to improve data accuracy.

1.3. **Geometric Correction:** Aligns imagery spatially to ensure accurate overlay with maps and other datasets.

1.4. **Cloud Masking:** Identifies and excludes cloud-contaminated pixels to prevent data inaccuracies.

2. **Image Analysis Techniques**

2.1. **Vegetation Index Calculation:** Derivation of indices such as NDVI, EVI, and SAVI to quantify vegetation health.

2.2. **Classification Methods:** Application of supervised and unsupervised classification algorithms to delineate crop types and stress zones.

2.3. **Change Detection:** Temporal comparison to identify onset and progression of crop stress or nutrient deficiencies.

2.4. **Machine Learning and Artificial Intelligence:** Utilization of algorithms such as Random Forest, Support Vector Machines (SVM), and deep learning for enhanced feature extraction, pattern recognition, and stress detection.

Case Studies and Applications

1. **Nitrogen Management in Cereals**

NDVI-based remote sensing has been successfully applied to assess nitrogen status in cereal crops, guiding variable rate nitrogen fertilization. This approach improves nitrogen use efficiency (NUE), increases yields, and reduces nitrogen-related greenhouse gas emissions.

2. **Phosphorus and Potassium Deficiency Detection**

Hyperspectral remote sensing has enabled early identification of phosphorus and potassium deficiencies in crops such as maize and wheat, allowing targeted nutrient interventions.

3. **Micronutrient Monitoring**

Spectral signatures derived from remote sensing data have been utilized to detect micronutrient deficiencies, including zinc and iron, in rice and other staple crops, facilitating timely corrective measures.

4. **Disease and Pest Stress Differentiation**

Advanced spectral and thermal imaging techniques assist in distinguishing nutrient stress from biotic stresses such as disease and pest attacks, improving diagnostic accuracy and management decisions.

Challenges and Limitations

1. **Spectral Confounding Factors**

Variability in soil background, moisture content, and canopy architecture can confound spectral signals, complicating accurate interpretation of nutrient status.

2. **Spatial and Temporal Resolution Trade-offs**

High spatial resolution data often have lower temporal frequency, limiting the ability to monitor rapid changes, whereas frequent data acquisitions may have coarser spatial resolution.

3. **Calibration and Validation Requirements**

Ground truth data collection is essential for calibrating and validating remote sensing-derived assessments but can be resource-intensive and laborious.

4. **Data Processing Complexity**

Advanced data processing and analysis require specialized expertise and computational resources, potentially limiting accessibility.

5. **Cost and Accessibility**

High-resolution satellite imagery and UAV platforms may be cost-prohibitive for smallholder farmers and resource-limited settings.

Emerging Trends and Future Perspectives

1. **Integration of Multi-Source Data**

Combining satellite, UAV, and proximal sensing data enhances spatial and temporal coverage, improving accuracy and reliability of crop health assessments.

2. **Advances in Hyperspectral Sensor Technology**

Miniaturization and cost reduction of hyperspectral sensors are enabling broader adoption, facilitating detailed nutrient and stress diagnosis.

3. **Real-Time Monitoring and Cloud Computing**

Integration of IoT-enabled sensors, cloud computing, and big data analytics enables near real-time crop health monitoring and decision support.

4. **Artificial Intelligence and Machine Learning**

Enhanced pattern recognition and predictive modeling capabilities improve nutrient stress diagnosis and management recommendations.

5. **Seamless Integration with Precision Agriculture**

Linking remote sensing data with automated machinery and VRT systems enables responsive nutrient management, optimizing input use and minimizing environmental impact.

Conclusion

Remote sensing techniques constitute indispensable tools for crop health assessment and precision nutrient management. By leveraging spectral, thermal, and structural data, these technologies enable early detection of nutrient deficiencies, facilitate site-specific input application, and enhance resource use efficiency. Despite challenges related to data acquisition, processing, and interpretation, ongoing technological advancements and integration with precision agriculture systems promise substantial improvements in sustainable crop production and environmental stewardship.

References

Gorai, T., Yadav, P. K., Choudhary, G. L., & Kumar, A. (2021). Site-specific crop nutrient management for precision agriculture—A review. *Curr. J. Appl. Sci. Technol*, *40*(10), 37-52.

Sishodia, R. P., Ray, R. L., & Singh, S. K. (2020). Applications of remote sensing in precision agriculture: A review. *Remote sensing*, *12*(19), 3136.

Singh, K. K., Kumar, A., Dheer, V., Yadav, K. K., & Sachan, K. (2023). Remote sensing for precise nutrient management in agriculture. *Vigyan Varta an International E-Magazine for Science Enthusiasts*, *3*, 71-75.

Gajbhiye, M., Agrawal, K. K., Jha, A. K., Kumar, N., & Raghuwanshi, M. (2023). Crop health monitoring through remote sensing: A review. *International Journal of Environment and Climate Change*, *13*(10), 2581-2589.

Raza, I., Zubair, M., Zaib, M., Khalil, M. H., Haidar, A., Sikandar, A., ... & Ashfaq, M. A. (2023). Precision nutrient application techniques to improve soil fertility and crop yield: A review with future prospect. *International Research Journal of Educational and Tecnology*, *5*.

Swarnkar, S. K., Dewangan, L., Dewangan, O., Prajapati, T. M., & Rabbi, F. (2023, September). AI-enabled crop health monitoring and nutrient management in smart agriculture. In *2023 6th international conference on contemporary computing and informatics (IC3I)* (Vol. 6, pp. 2679-2683). IEEE.

AGRICULTURE BULLETIN
ISSN: 3049-2289

Weed management strategies for organic farming systems

Sachin Saini*, Vishnu Shanker Gancha, Omprakash Tak, Varsha Jeetarwal and Rahul
Ph.D. Scholar, Department of Agronomy, Agriculture University Jodhpur, Jodhpur, Rajasthan, India
Ph.D. Scholar, Department of Agronomy, Agriculture University Jodhpur, Jodhpur, Rajasthan, India
Ph.D. Scholar, Department of Agronomy, Agriculture University Jodhpur, Jodhpur, Rajasthan, India
Ph.D. Scholar, Department of Agronomy, Rajasthan Agricultural Research Institute, Durgapura, Jaipur, Rajasthan, India
Ph.D. Scholar, Department of Agronomy, Rajasthan Agricultural Research Institute, Durgapura, Jaipur, Rajasthan, India

Introduction

Weed management is a fundamental aspect of organic farming systems, playing a crucial role in ensuring optimal crop growth and yield. Weeds compete directly with crops for essential resources such as nutrients, water, light, and space, which can significantly diminish crop productivity and quality. Unlike conventional farming, which often relies heavily on synthetic herbicides for weed control, organic farming prohibits such chemical inputs due to environmental, health, and sustainability concerns. This restriction necessitates the adoption of alternative, integrated weed management strategies that align with organic principles. Effective weed management in organic systems, therefore, depends on a combination of cultural, mechanical, biological, and preventive practices that not only suppress weed populations but also enhance soil health, biodiversity, and long-term sustainability of the agroecosystem.

2. Principles of Weed Management in Organic Farming

Organic weed management is guided by several core principles that emphasize sustainability, ecological balance, and crop health. These principles focus on preventing weed establishment, disrupting weed life cycles, and enhancing the competitive ability of crops against weeds. Key principles include:

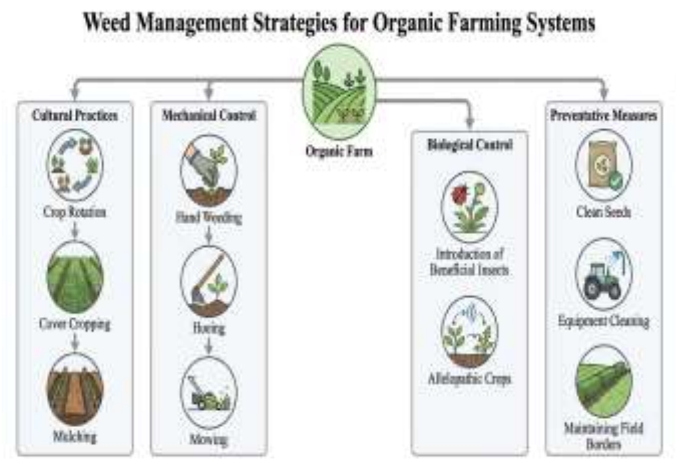


Figure 1: Weed management strategies for organic farming systems

a) **Prevention:** The foremost strategy involves preventing weed establishment through the use of clean seeds, equipment sanitation, and maintaining field hygiene. Preventing weed seed introduction reduces the initial weed seed bank and limits future infestations.

b) **Diversity:** Implementing diverse crop rotations and intercropping systems reduces weed adaptability by varying environmental conditions and cropping patterns, thus preventing weeds from becoming dominant.

c) **Soil Health:** Maintaining fertile, well-structured soils supports vigorous crop growth, which in turn suppresses weed emergence by shading and nutrient competition.

d) **Mechanical and Cultural Control:** Employing physical methods such as tillage, hoeing, and mulching combined with agronomic practices like planting density adjustments to reduce weed pressure.

e) **Biological Control:** Utilizing natural weed antagonists, including allelopathic plants and biological agents, to suppress weed populations without harming crops or the environment.

Table 1: Types of Weed Management Strategies in Organic Farming

Strategy Type	Method	Description	Advantage	Limitation
Cultural Control	Crop rotation	Alternating crops to disrupt weed cycles	Reduces weed pressure naturally	Requires planning
Cultural Control	Cover cropping	Use of legumes/green manures	Suppresses weeds, improves soil	Competition for nutrients
Mechanical Control	Tillage/hand weeding	Physical removal of weeds	Immediate effect	Labor-intensive
Mechanical Control	Mulching	Organic residues/plastic mulch	Blocks weed emergence	Cost of materials
Biological Control	Bioherbicides	Use of microbes/insects	Eco-friendly	Limited availability
Preventive Control	Clean seeds, sanitation	Avoid weed introduction	Long-term control	Requires strict monitoring

3. Cultural Weed Management Strategies

3.1 Crop Rotation

Crop rotation is a cornerstone of cultural weed management in organic farming. By alternating crops with differing growth habits, planting dates, and canopy structures, crop rotation disrupts the life cycles of weed species adapted to specific conditions. For example, rotating between cereals and broadleaf crops changes soil microclimate and nutrient dynamics, making it difficult for certain weeds to establish consistently. Including cover crops within rotations further suppresses weeds by competing for resources and altering soil conditions. Crop rotation also reduces the buildup of weed seed banks by preventing weed species from completing their reproductive cycles year after year.

3.2 Cover Cropping

Cover crops play a multifaceted role in weed management by providing soil cover that shades out weed seedlings, competing vigorously for nutrients and moisture, and releasing allelopathic compounds that inhibit weed seed germination and growth. Leguminous cover crops such as clover and vetch contribute to nitrogen fixation, improving soil fertility while suppressing weeds. Grasses like rye and oats produce dense biomass that physically blocks weed emergence. Brassicas such as mustard release glucosinolates that act as biofumigants to reduce weed seed viability. The choice of cover crop

ISSN: 3049-2289

species, planting time, and termination method are critical to maximizing weed suppression without negatively impacting subsequent cash crops.

3.3 Crop Density and Planting Patterns Optimizing crop density and planting arrangements enhances crop competitiveness by reducing the available niche space for weeds. Increasing plant density creates a more closed canopy, reducing light penetration to the soil surface and limiting weed seed germination and growth. Narrow row spacing and intercropping systems encourage rapid canopy closure and improve resource use efficiency. Intercropping, where two or more crops are grown simultaneously, can exploit complementary growth habits to suppress weeds more effectively than monocultures. For instance, planting tall, fast-growing crops alongside low-growing species creates vertical stratification that limits weed establishment.

3.4 Mulching

Mulching involves applying a layer of organic material such as straw, wood chips, compost, or leaves on the soil surface to suppress weed emergence by blocking sunlight and creating a physical barrier. Mulches also conserve soil moisture, moderate soil temperature, and contribute to soil organic matter as they decompose. The selection of mulch type and thickness is important; too thick a layer may inhibit crop emergence or harbor pests, while too thin may be ineffective against weeds. Organic mulches also promote beneficial soil organisms that contribute to nutrient cycling and soil structure improvement.

4. Mechanical Weed Control

4.1 Hand Weeding

Hand weeding remains a highly effective and selective method of weed control in organic farming, particularly for high-value crops and small-scale operations. It allows precise removal of weeds without disturbing the soil excessively, thus preserving soil structure and microbial communities. While labor-intensive, hand weeding is essential for managing weeds in row crops, transplant beds, and areas where mechanical tools cannot operate effectively.

4.2 Hoeing and Cultivation

Mechanical cultivation using hoes, rotary cultivators, harrows, and other implements uproots or buries young weed seedlings, preventing their establishment. Timing is critical; cultivation is most effective when weeds are small and before crop roots are damaged. Shallow tillage is preferred to minimize soil disturbance, reduce erosion risk, and avoid bringing buried weed seeds to the surface. Regular cultivation interrupts weed growth cycles and reduces seed production.

4.3 Flame Weeding

Flame weeding applies controlled heat to above-ground weed tissues, causing rapid desiccation and death. It is particularly effective against small, annual weeds and can be used between crop rows without soil disturbance. Flame weeding is a chemical-free method that preserves soil microbial health but requires careful operation to avoid crop damage and fire hazards. It is especially useful in organic vegetable production and nursery settings.

4.4 Mowing and Cutting

Mowing reduces the biomass and seed production of perennial weeds and cover crops, weakening their root reserves over time. Frequent cutting prevents weeds from flowering and setting seed, gradually reducing weed populations. This method is often integrated with grazing or other control measures to achieve sustainable management of perennial weed species.

5. Biological Weed Control

5.1 Allelopathy

Allelopathy involves the release of natural biochemicals by certain plants that inhibit weed seed germination and growth. Incorporating allelopathic cover crops such as rye, sorghum, or mustard into rotations can suppress weed populations by creating unfavorable soil chemical environments. These compounds can persist in the soil, providing residual weed suppression effects. Understanding allelopathic interactions is essential for selecting appropriate species and timing their use to maximize benefits.

5.2 Natural Enemies

Biological control agents such as insects, fungi, or pathogens that specifically target weed species offer environmentally friendly weed suppression options. While more established in rangeland and perennial cropping systems, research is advancing to adapt these methods for row crops in organic farming. Examples include fungal pathogens that infect weed seeds or insects that feed on weed foliage. Successful application requires detailed knowledge of weed biology and the ecology of control agents.

5.3 Grazing

Livestock such as goats, sheep, and cattle can be used strategically to control weeds through defoliation and trampling. Targeted grazing reduces weed biomass and seed production, especially for woody or perennial species. Grazing must be carefully managed to avoid crop damage, soil compaction, and nutrient imbalances. Integrating grazing into crop rotations can enhance nutrient cycling and soil fertility while controlling weeds.

6. Preventive and Sanitation Measures

6.1 Clean Seed and Planting Material

Using certified weed-free seeds and transplants is a fundamental preventive measure to avoid introducing weed seeds into the field. Seed cleaning, treatment, and inspection reduce contamination risks. Starting with clean planting material lowers the weed seed bank and reduces the need for intensive control measures later.

6.2 Equipment Hygiene

Weed seeds and propagules can easily spread via farm machinery and tools. Regular cleaning of equipment between fields prevents cross-contamination and reduces the spread of invasive or problematic weed species. Equipment hygiene practices include washing, brushing, and disinfection.

6.3 Field Border Management

Maintaining weed-free field margins, buffer zones, and pathways limits weed seed influx from adjacent uncultivated areas or neighboring farms. Border management includes mowing, targeted herbicide use (where permitted), or planting competitive vegetation to act as a barrier. This reduces weed pressure within the crop field and helps contain infestations.

6.4 Timing of Operations

Adjusting the timing of planting, cultivation, and harvesting operations can exploit vulnerable stages in weed life cycles. For example, early planting may give crops a competitive advantage by establishing before weed emergence. Similarly, timely cultivation can target weed seedlings before they mature. Synchronizing farm activities with weed biology enhances control efficacy.

7. Integration of Weed Management Practices

An integrated weed management (IWM) approach combines multiple strategies tailored to specific cropping systems, weed species, and local environmental conditions. IWM recognizes that no single method is sufficient for sustainable control but that combining cultural, mechanical, biological, and preventive measures creates synergistic effects. For example, a rotation including cover crops, narrow row spacing, timely shallow cultivation, and hand weeding can collectively reduce weed seed banks and suppress weed growth sustainably. Continuous monitoring of weed populations and adaptive management are critical components of IWM, allowing farmers to respond dynamically to changing weed pressures and environmental factors.

8. Challenges and Considerations

Organic weed management faces several challenges that require careful consideration:

a) **Labor Intensity:** Many organic methods, such as hand weeding and mechanical cultivation, demand significant labor inputs, which may limit scalability or increase production costs.

b) **Soil Disturbance:** Repeated mechanical control can disrupt soil structure, reduce microbial diversity, and increase erosion risk if not managed properly.

c) **Weed Adaptation:** Although chemical resistance is not a concern, some weed species may adapt to cultural practices, necessitating ongoing diversification of strategies.

d) **Economic Costs:** Balancing the cost-effectiveness of weed control measures with their efficacy is essential for farmer adoption and profitability.

e) **Knowledge and Skill Requirements:** Effective implementation requires understanding weed biology, ecology, and management techniques, highlighting the need for farmer training and extension support.

9. Advances and Innovations

Recent advances in organic weed management focus on improving efficiency and sustainability:

a) **Precision Agriculture:** Sensor-guided mechanical weeders and robotic tools enable targeted weed control, reducing labor and soil disturbance.

b) **Novel Cover Crops:** Breeding and selecting cover crop species with enhanced allelopathic properties or rapid biomass production improve weed suppression.

c) **Bioherbicides:** Development of natural product-based herbicides derived from microbial or plant sources offers targeted, environmentally benign weed control options.

d) **Competitive Crop Varieties:** Breeding crops with traits such as rapid early growth, dense canopies, or allelopathic potential enhances crop competitiveness against weeds.

10. Conclusion

Weed management in organic farming systems requires a comprehensive, integrated approach that balances prevention, cultural practices, mechanical control, and biological methods. Such strategies promote sustainable crop production by reducing weed pressure, enhancing soil health, and maintaining agroecosystem balance. Continued research, innovation, and farmer education are vital to improving the effectiveness and adoption of organic weed management practices, ensuring the long-term viability of organic agriculture.

References

Liebman, M., & Davis, A. S. (2009). Managing weeds in organic farming systems: an ecological approach. *Organic farming: the ecological system*, *54*, 173-195.

Bàrberi, P. A. O. L. O. (2002). Weed management in organic agriculture: are we addressing the right issues?. *Weed research*, *42*(3), 177-193.

Pantović, J. G., & Sečanski, M. (2023). Weed control in organic farming. *Contemporary Agriculture*, *72*(1-2), 43-56.

Brown, B., & Gallandt, E. R. (2018). A systems comparison of contrasting organic weed management strategies. *Weed Science*, *66*(1), 109-120.

ISSN: 3049-2289

Anderson, R. L. (2015). Integrating a complex rotation with no-till improves weed management in organic farming. A review: RL Anderson. *Agronomy for sustainable development*, *35*(3), 967-974.

Pupalienė, R., Sinkevičienė, A., Jodaugienė, D., & Bajorienė, K. (2015). Weed Control by Organic Mulch in Organic Farming. *Weed biology and control*, 65-86.

Watson, C. A., Atkinson, D., Gosling, P., Jackson, L. R., & Rayns, F. W. (2002). Managing soil fertility in organic farming systems. *Soil use and management*, *18*, 239-247.

AGRICULTURE BULLETIN
ISSN: 3049-2289

Agriculture as the Driver of Rural Development

Vyomendra Kumar Singh, Madri , Dr. Prakash Yadav & Shivani Kumari
1.Ph. D. Scholar, School of Agricultural Sciences & Engineering, IFTM University, Moradabad-244102
2.Assistant Professor, School of Agriculture Science ,Motherhood University Roorkee -247661
3. Assistant Professor, COA, Gonda (ANDUAT, Ayodhya)-271502
4. Ph. D. Scholar, School of Agriculture Science,Nagaland University ,Medziphema Campus,Nagaland-797106

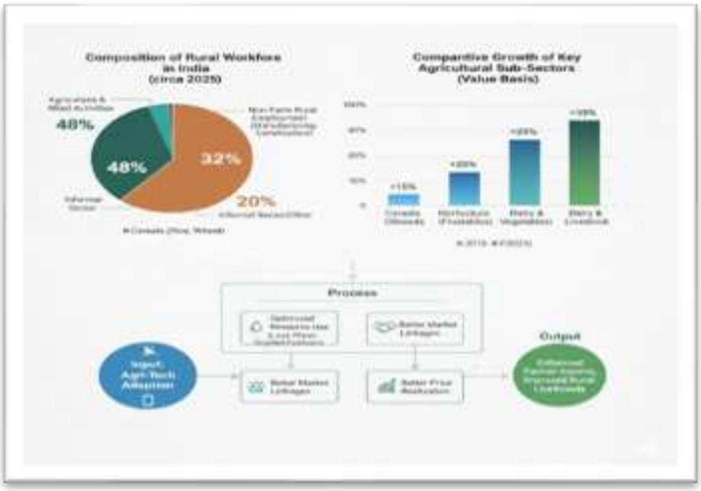
India as a nation where over 65% of the population resides in villages, rural prosperity is highly linked to agricultural productivity. By analyzing current trends like "Agri-tech" integration, the shift toward high-value crops, and recent policy frameworks such as the Prime Minister Dhan-Dhaanya Krishi Yojana (2025-26), this paper highlights how agriculture transcends food production to drive infrastructure, employment, and social equity.

➢ The Socio-Economic Backbone

In India, agriculture serves as the primary source of livelihood for millions. Beyond direct farming, it fuels a massive "allied" ecosystem including livestock, fisheries, and forestry.

Employment Multiplier: For every 1% growth in agricultural output, there is a significant ripple effect in rural non-farm sectors such as transport, processing, and retail.

Poverty Alleviation: Academic research consistently shows that agricultural growth is at least twice as effective in reducing poverty as growth in other sectors, primarily because it directly impacts the lowest income brackets in rural clusters.



➢ Modern Drivers: Diversification and Agri-Tech

The traditional "Green Revolution" model of cereal-centric farming is evolving into a more resilient, diversified system.

Crop Diversification: There is a strategic shift toward High-Value Crops (HVCs) like horticulture (fruits/vegetables), which offer higher returns per hectare and are more labor-intensive, addressing rural underemployment.

Digital Integration: By 2026, the adoption of AI-driven advisory services and satellite-based crop monitoring bridged the information gap. Farmers now use real-time data to optimize input costs, directly increasing the "disposable income" within rural households.

This image illustrates the impact of agri-tech adoption:

ISSN: 3049-2289

➢ **Institutional Catalysts and Policy Frameworks**

Rural development is currently being accelerated by targeted government interventions aimed at "Aatmanirbharta" (Self-reliance).

Infrastructure Development: Programs like the Agriculture Infrastructure Fund (AIF) are building cold storage and supply chains, reducing post-harvest losses which previously stood at nearly 15-20%.

PM Dhan-Dhaanya Krishi Yojana (2025-26): Launched to target 100 low-productivity districts, this initiative focuses on "More Crop Per Drop" through micro-irrigation and enhancing credit parameters for marginal farmers.

➢ **The Sustainability Paradox**

Despite its potential, Indian agriculture faces a "Sustainability Paradox." While productivity must rise to feed a growing population, climate change and fragmented landholdings (average size <1.2 hectares) pose existential threats.

➢ **Expansion of Agricultural Activities**

As economies grow, there is an increasing demand for diverse agricultural products. This leads to the expansion of agricultural activities into new markets and the adoption of modern techniques to increase productivity and meet market demands.

Climate Resilience: Erratic monsoons and heatwaves require a transition to "Climate-Smart Agriculture."

Land Fragmentation: Small farm sizes prevent economies of scale, making the role of Farmer Producer Organizations (FPOs) critical for collective bargaining and mechanization.

Agriculture remains the "first engine" of India's development journey. The transition from subsistence farming to a technology-backed, market-linked enterprise is the key to stopping forced migration from villages to cities. For rural India to be truly developed, agriculture must be viewed not as a legacy of the past, but as a high-tech, profitable, and sustainable pillar of the future.

AGRICULTURE BULLETIN
ISSN: 3049-2289

Is sustainable Agriculture possible without reducing food production?

Madri Vyomendra Kumar Singh, Dr. Prakash Yadav & Shivani Kumari
1.Assistant Professor, School of Agriculture Science ,Motherhood University Roorkee -247661
2.Ph. D. Scholar, School of Agricultural Sciences & Engineering, IFTM University, Moradabad-244102
3. Assistant Professor, COA, Gonda (ANDUAT, Ayodhya)-271502
4. Ph. D. Scholar, School of Agriculture Science,Nagaland University ,Medziphema Campus,Nagaland-797106

The global food system faces the dual challenge of rising food demand while reducing environmental degradation caused by conventional agricultural practices. Sustainable agriculture is often perceived as incompatible with high productivity, raising concerns about potential trade-offs between sustainability and food production. Drawing on evidence from sustainable intensification, agroecology, soil health science, agroforestry, and systems-based approaches, the study finds that maintaining or increasing food production while enhancing environmental sustainability is feasible. However, success depends on integrated management practices, enabling policies, and socio-economic support systems. The article concludes that sustainable agriculture does not require reduced production but rather a redefinition of productivity that incorporates ecological resilience and long-term resource efficiency.

Agriculture is a fundamental driver of global food security but is also a major contributor to environmental degradation, including biodiversity loss, greenhouse gas emissions, soil degradation, and water scarcity. With the global population projected to exceed 9 billion by mid-century, food production must increase substantially. This raises a critical question: Can agriculture become environmentally sustainable without reducing food production?

Historically, agricultural intensification has increased yields but often at the expense of ecosystem health. In response, sustainable agriculture has emerged as a framework that integrates environmental stewardship, economic viability, and social equity. Critics argue that sustainability-oriented practices may compromise yields, while proponents suggest that productivity and sustainability can be mutually reinforcing. This article synthesizes current academic research to evaluate these claims through a holistic lens.

How to Increase Sustainable Agriculture practice and Productivity

- **Sustainable Agriculture**

Sustainable agriculture is defined as a system of food and fiber production that maintains its economic viability while conserving natural resources and supporting social well-being over the long term. Core dimensions include:

Environmental sustainability (soil, water, biodiversity, climate)

Economic sustainability (farmer livelihoods, efficiency)

ISSN: 3049-2289

Social sustainability (food security, equity, resilience)

➢ Sustainable Intensification

Sustainable intensification (SI) is a key concept underpinning the compatibility of sustainability and productivity. SI aims to increase or maintain yields from existing farmland while reducing negative environmental impacts. Rather than expanding agricultural land, SI focuses on efficiency, innovation, and ecological processes.

➢ Evidence from Scientific Literature

Soil Health and Yield Stability

Soil health is widely recognized as the foundation of sustainable productivity. Research demonstrates that practices such as reduced tillage, organic amendments, crop rotations, and cover cropping improve soil structure, microbial activity, and nutrient cycling. These improvements enhance yield stability and resilience to climate variability without reducing output.

Healthy soil also improves water infiltration and retention, reducing vulnerability to droughts and floods while supporting long-term productivity.

➢ Crop Diversification and Agroecology

Agroecological approaches, including crop diversification, intercropping, and integrated crop–livestock systems, have been shown to maintain comparable yields to monoculture systems over time. While short-term yield reductions may occur during transition periods, long-term studies indicate improved system resilience, reduced pest pressure, and greater nutrient-use efficiency.

Diversified systems also enhance ecosystem services such as pollination, biological pest control, and nutrient recycling, which indirectly support sustained production.

➢ Agroforestry and Integrated Landscapes

Agroforestry systems integrate trees with crops and/or livestock, creating multifunctional landscapes. Empirical evidence shows that agroforestry improves soil fertility, reduces erosion, sequesters carbon, and increases overall system productivity per unit area when all outputs are considered (food, fodder, fuel, timber).

These systems contribute to food security not by maximizing a single crop yield, but by optimizing total system productivity and resilience.

➢ Resource-Use Efficiency and Technology

Advances in precision agriculture, improved crop varieties, and efficient nutrient and water management allow farmers to produce more food with fewer inputs. Improved nitrogen-use efficiency, for example, reduces emissions while maintaining yields. Technological innovations, when combined with ecological practices, support sustainability without yield penalties.

➢ Socio-Economic and Policy Dimensions

While biophysical evidence supports sustainable productivity, adoption is constrained by socio-economic factors. Barriers include:

- High initial investment costs
- Limited access to knowledge and extension services
- Inadequate policy incentives
- Market structures that favor short-term yield maximization

Supportive policies, research investments, and farmer-centered extension systems are essential to

ISSN: 3049-2289

scaling sustainable practices without compromising production.

- **Holistic Systems Perspective**

The literature increasingly emphasizes that no single practice guarantees sustainability with productivity. Instead, a systems-based approach requires integrating:

- Farm-level practices (soil, crops, livestock)
- Landscape-level planning (biodiversity, water)
- Policy and market mechanisms
- Knowledge exchange and innovation

Sustainable agriculture must be evaluated not only by yield per crop, but by long-term system performance, environmental outcomes, and food system resilience. Evidence demonstrates that environmentally sound practices can maintain or enhance yields while improving soil health, biodiversity, and climate resilience. The perceived trade-off between sustainability and productivity arises largely from short-term or narrow yield-based assessments.

Achieving sustainable agriculture at scale requires a holistic redefinition of productivity—one that values ecosystem services, resilience, and long-term food security alongside yield. With appropriate policies, technological support, and knowledge dissemination, sustainable agriculture can meet global food demands while safeguarding the environment for future generations.

AGRICULTURE BULLETIN
ISSN: 3049-2289

The Role of Agriculture in Building Viksit Bharat 2047

Vyomendra Kumar Singh, Madri[2] , Dr. Prakash Yadav & Shivani Kumari
1.Ph. D. Scholar, School of Agricultural Sciences & Engineering, IFTM University, Moradabad-244102
2.Assistant Professor, School of Agriculture Science, Motherhood University Roorkee -247661
3. Assistant Professor, COA, Gonda (ANDUAT, Ayodhya)-271502
4. Ph. D. Scholar, School of Agriculture Science, Nagaland University ,Medziphema Campus, Nagaland-797106

As India sets its sights on becoming a developed nation (Viksit Bharat) by the centenary of its independence in 2047, the agricultural sector stands as the most critical determinant of inclusive growth. By transitioning from subsistence farming to high-value, data-driven agri-business, India can secure food sovereignty, achieve $100 billion in exports, and bridge the urban-rural income gap.

- **The Macro-Economic Imperative**

For India to reach a $30 trillion economy by 2047, the agricultural sector must maintain a steady growth rate of 4% or higher. While its share of GDP may naturally decrease as industry expands, its role as a "socio-economic stabilizer" is irreplaceable.

Employment Elasticity: Agriculture currently supports nearly 45% of the population. A "Viksit" status requires shifting surplus labor to agri-processing, rather than just urban migration.

Capital Injection: The vision for 2047 involves a shift from "Price Support" (subsidies) to "Investment Support" (infrastructure).

- **Digital Public Infrastructure (DPI): The "Agri-Stack" Revolution**

The hallmark of a developed nation is the formalization of its economy. The Digital Agriculture Mission is the cornerstone of this transformation:

AgriStack: A unified database providing every farmer with a digital ID linked to land records, crop insurance, and credit history. This eliminates middle-men and enables Direct Benefit Transfer (DBT).

Precision Agriculture: Using the "Internet of Things" (IoT), farmers can monitor soil health in real-time.

Equation of Efficiency: Output \propto (Tech \times Resource Optimization).

AI-Driven Forecasting: Predictive analytics for weather and pest outbreaks reduce the "risk premium" associated with Indian farming, making it an attractive sector for bank lending.

- **Structural Shifts: Diversification and Allied Sectors**

To reach developed-nation income levels, the Indian farm must move beyond cereal-centric (Rice/Wheat) production.

- **Climate-Smart Agriculture (CSA)**

A developed India must be a sustainable India. With rising temperatures, the 2047 roadmap emphasizes Resilience:

Micro-Irrigation: Shifting from "Flood Irrigation" to "Drip/Sprinkler" systems. This is critical as India holds only 4% of the world's freshwater but 18% of its population.

Biofortification: Developing seeds that are not only drought-resistant but also enriched with Zinc, Iron, and Protein to solve the "Hidden Hunger" (malnutrition) challenge.

ISSN: 3049-2289

Natural Farming: Reducing chemical dependency to restore soil carbon, ensuring the land remains productive for the next century.

- **Post-Harvest Logistics and Global Value Chains**

A major hurdle to Viksit Bharat is the 20-30% waste in the supply chain.

Structural & Resource-Based Issues (Affecting Production Capacity)

- Fragmented Land Holdings: The fragmentation of land holdings remains a significant barrier to agricultural productivity in India.
- Small and marginal farmers, over 85% of India's agricultural population, cultivate nearly 45% of the net sown area (Agricultural Census 2015-16). Yet, small landholdings yield insufficient returns for a decent livelihood.
- Small landholdings hinder mechanization, lead to inefficient use of inputs, and lower overall productivity.
- Poor Irrigation Infrastructure: Despite efforts like the Pradhan Mantri Krishi Sinchai Yojana (PMKSY), Irrigation remains highly dependent on monsoons. About 61% of India's farmers rely on rain-fed agriculture and 55% of the gross cropped area is under rain-fed farming, making it vulnerable to climate change.
- Inadequate irrigation infrastructure exacerbates water scarcity and limits crop production during dry periods.
- Land acquisition is a major bottleneck for large-scale irrigation projects. Also, the heavy subsidies on power for agriculture have incentivized the over-pumping of groundwater, further compounding the water scarcity issue.
- Persistent Dependence on Chemical Fertilizers: Overreliance on chemical fertilizers, while boosting yields in the short term, is causing long-term soil degradation and environmental damage.
- India is the second-largest consumer of fertilizers globally. In 2023-24, the total annual consumption was around 601 lakh metric tonnes (LMT).
- India's extensive use of fertilizers contributes to soil health depletion and has led to declining per hectare productivity in certain regions.
- The PM Gati Shakti National Master Plan: Integrating railways, highways, and ports specifically for "Krishi Udan" (air transport for perishables) and "Kisan Rails."
- Farmer Producer Organizations (FPOs): Small farmers are being aggregated into "Companies" to give them the bargaining power of a corporation. This "Scale of Economy" is essential for global competitiveness.

India's journey from a food-deficient economy to a global agricultural powerhouse now demands a leap from food security to farmer prosperity, and from plough to platform. To realizethe vision of Viksit Bharat, agriculture must evolve into a tech-integrated, climate-resilient, and value-driven sector. This calls for a shift beyond the Green Revolution to evergreen solutions, where soil meets software, and innovation coexists with inclusivity. By seeding Viksit Bharat from rural roots, India can ensure that agriculture not only feeds the nation but also fuels its transformation into a developed economy.

The journey to Viksit Bharat 2047 is a journey of dignity for the Indian farmer. Agriculture is the bridge between India's past and its prosperous future. By marrying traditional wisdom (soil health, biodiversity) with frontier technology (AI, Drones, Biotech), India will not only feed its 1.6 billion citizens but will emerge as the "Food Provider to the World.

AGRICULTURE BULLETIN
ISSN: 3049-2289

Advancing Pest Surveillance Through Mobile Applications and Digital Technologies

Nandit E K[1] and Pooja Naduvalath[2]
[1]PG Research Scholar, Department of Agricultural Entomology, College of Agriculture, Padannakkad, Kasaragod, Kerala -671314, India.
[2]PG Research Scholar, Department of Plant Pathology, College of Agriculture, Padannakkad, Kasaragod, Kerala -671314, India.

Digital pest surveillance is emerging as a transformative approach to pest management in agriculture by replacing conventional manual scouting with faster, more accurate, and technology-driven monitoring systems. It uses mobile applications, artificial intelligence, machine learning, remote sensing, geographic information systems, Internet of Things devices, and cloud-based platforms to detect, identify, map, and predict pest occurrence in fields, orchards, greenhouses, and storage areas. These tools enable farmers to upload pest images or field observations, receive automated pest identification and severity assessment, and obtain timely, location-specific advisory recommendations for eco-friendly pest control. Digital pest surveillance improves early detection, supports precision pest management, reduces unnecessary pesticide use, and generates valuable data for research and forecasting. Its relevance is increasing under climate change, rising food safety concerns, and the growing demand for sustainable and precision agriculture. However, adoption is still constrained by poor rural connectivity, digital illiteracy, limited region-specific pest databases, and the high cost of advanced technologies. Despite these challenges, the future of digital pest surveillance is promising, especially with the integration of AI, IoT, drones, national surveillance networks, and farmer-friendly multilingual and voice-based advisory systems.

Introduction

The Earth is a special planet with a wide variety of life forms. Among all life forms on Earth, Insects dominate the land with an estimated quintillion of them present on our planet. They represent over 90% of all animal life and outnumber humans by a factor of 1.4 billion for every single human. Over one million species of insects have been identified so far. However, there are still many species of insects waiting to be discovered. Insects inhabit almost every type of environment on Earth. This includes extreme climates like Antarctica, where there is a species of wingless midge. This is due to their small size, rapid reproduction rate, and their capacity to adapt to different environmental conditions. Because of these characteristics, they inhabit almost every type of environment.

Insect pests are those insect species that are harmful when their numbers are large and affect human welfare, convenience, or economic return. Insect pests damage crops, livestock, and stored commodities, and can also cause diseases. The main characteristics of insect pests are their economic damage, and it is estimated that fewer than 1% of all insect species are pests. Insect pests damage crops by consuming different parts of plants using their mouthparts, which are adapted for chewing or sucking. They also damage stored commodities, which are of poor quality and quantity, and can cause diseases by biting humans or spreading diseases. It is estimated that insect pests cause a loss of 18-20% in global crop production, and an additional loss of 10% during storage. The loss can range from 15-50% or more in the fields.

Insect pests are a significant problem in agriculture, which results in considerable yield loss worldwide.

ISSN: 3049-2289

Pest management is a key factor in agriculture, which can be achieved by timely and accurate information on the presence of insect pests in the field, traditionally achieved through manual scouting of the field. However, manual scouting also has certain limitations, which can be addressed with the advent of digital technologies in agriculture, which are shifting towards precision farming with the help of mobile apps, which can be used for efficient management of insect pests with the help of technologies such as artificial intelligence, remote sensing, cloud computing, and geographic information systems (GIS).

Digital Pest Surveillance

Digital Pest Surveillance is a technology-based approach for the surveillance of pest occurrence in fields, orchards, greenhouses, or storage areas using digital technologies such as mobile apps, sensors, cameras, IoT devices, remote sensing, AI/ML analytics, etc. This approach replaces traditional methods of pest surveillance using conventional methods of manual pest surveillance. The purpose of using the Digital Pest Surveillance approach in agriculture is to detect pest occurrence in fields, predict pest occurrence in fields, and provide advisory support for taking preventive measures before pest occurrence in fields.

These key components include data collection, data processing, data storage, and decision support. This system works by helping farmers collect pest image information or field information through a mobile application. This information is then processed using artificial intelligence and database technologies to identify the pest and its corresponding severity level (low, medium, or high). Based on the information obtained from the system, the farmer can instantly receive the appropriate recommendations for decision-making, including the effective and eco-friendly practices for pest management.

Key Digital Tools

A. Mobile Applications

Mobile applications serve as the main interface for communication between the farmer and digital agriculture technologies. The apps are developed in a way that they are easy for even the smallest of farmers, who own marginal farms, to use and access advanced technologies through a smartphone.

Detailed Features:

- Images for identifying pests: The app will help the farmer identify the pest infestation by taking a picture of the plant or the pest, and the app will diagnose the problem immediately.
- GPS for mapping fields: This feature will help the farmer identify the location of the infestation, which will help in taking appropriate measures for that location.
- Recording pest populations: The farmer will be able to manually input the population of the pests, which will help in understanding the dynamics of the pests over a period of time.
- Notifications for advisories: The app will provide real-time alerts for the outbreak of pests, weather conditions, and appropriate measures for the pests.

Some examples of such apps include Plantix, which uses AI for diagnosing pests and diseases through an image of the plant, and providing suggestions for treatment, and Kisan Suvidha, which provides weather updates, alerts for pests, and expert advice.

B. Artificial Intelligence (AI) and Machine Learning

The main technologies used for automation in pest surveillance and management are Artificial Intelligence and Machine Learning. These help in quick and accurate analysis of huge amounts of data.

How It Works:

- AI models are used to process huge amounts of image data related to pests and infected plants.
- The system recognizes different patterns like shape, size, color, and damage done by pests.
- Machine learning helps improve accuracy with increased data.
- AI models combine weather conditions, crop development stages, and historical records of pest infestations to forecast potential infestations.

Applications:

- Identifying major pests like aphids, whiteflies, jassids, and mealybugs.
- Prediction of pest infestations due to changing climatic conditions.
- Support for Integrated Pest Management (IPM) techniques.

Example: Microsoft uses AI-based agricultural initiatives to help farmers with data analytics and AI models. AI helps in minimizing human error and increases accuracy for proactive management of pests.

C. Remote Sensing and GIS

It involves the use of remote sensing and Geographic Information Systems (GIS) to monitor the large-scale occurrence of the pest.

Detailed Functions:

- Remote sensing: It uses satellite images, drones, etc., to take pictures of the crop fields, which helps to detect the symptoms of the occurrence of the pest.
- GIS: It uses the spatial data to analyse the pattern of the occurrence of the pest.
- Early warning systems: It detects the abnormal conditions of the crops before the symptoms are visible to the naked eye.
- Temporal analysis: It tracks the changes in the occurrence of the pest at different locations.

Example: The Indian Space Research Organisation uses satellite images to monitor the health of the crops.

These technologies are extremely useful to the policymakers and researchers.

D. IoT and Smart Traps

The Internet of Things (IoT) connects physical devices in the field with digital systems, allowing for automated data collection in real-time.

Smart Trap Mechanism:

- Deploys pheromones for attracting specific insect pests.
- Is provided with sensors or cameras for detecting and counting trapped pests.
- Automates data transmission to cloud servers or mobile applications.

Detailed Benefits:

- Enables continuous monitoring of pests without human intervention.
- Ensures accurate and unbiased information regarding pest populations.
- Reduces labour requirements for counting pests.
- Enables threshold-based decision-making for pest management.

IoT-based systems can increase efficiency and accuracy in pest management.

E. Cloud-Based Decision Support Systems

Cloud computing platforms are essential for data storage, data processing, and advisory generation.

Detailed Functions:

- Data integration: It integrates data collected from various sources, including weather stations, mobile applications, sensors, and satellite images.
- Big data analytics: It analyzes large quantities of data to determine trends and patterns.
- Predictive modelling: It forecasts pest occurrence and suggests preventive actions.
- Advisory generation: It offers personalized advisory to farmers depending on the location and conditions of the crops.

Food and Agriculture Organization of the United Nations advocates for the use of digital agriculture platforms to encourage sustainable agriculture practices.

Advantages

Digital pest surveillance has several significant advantages in modern agriculture. It facilitates the early detection of pest infestations in their very initial stages. This helps to avoid severe damage to crops and reduce losses. It aids in precision pest management by enabling farmers to apply pesticides only where they are required. This reduces costs and pollution. It also facilitates real-time monitoring. This ensures that farmers receive continuous updates and act immediately. This helps to improve response time. It also promotes the use of fewer chemicals by facilitating eco-friendly practices like integrated pest management. This reduces the need for pesticide applications. It also generates large amounts of data. This is very useful for research on various aspects of pest management.

Relevance in Current Scenario

Climate change is affecting the life cycles, distribution, and outbreak of pests, including changes in the temperature and rainfall regime, thereby increasing the necessity to have predictive tools. The Digital India program has also helped to increase the usage of digital technologies in agriculture and has motivated farmers to adopt these digital technologies. At the same time, the advent of affordable smartphones has helped digital technologies reach the rural sector as well. The rise of food safety issues and the necessity to have safe food with reduced pesticide content are also motivating farmers to adopt precise and eco-friendly approaches to manage pests.

Challenges and Limitations

Some of the challenges and limitations of digital pest surveillance are discussed below. One of the major challenges of digital pest surveillance is technical issues, especially when internet connectivity is poor in rural areas. This would affect the efficiency of digital surveillance. Another limitation of digital surveillance is the knowledge gap, whereby many farmers might not be digitally literate enough to use apps and other online services. Another limitation of digital surveillance is data, whereby for digital surveillance to be effective, there should be regional data of pests. However, this is not always available, which would affect the efficiency of digital surveillance. Another limitation of digital surveillance is cost, whereby modern technologies such as drones, sensors, smart traps, and AI are expensive, making it difficult for many farmers, especially small and marginal farmers, to adopt digital surveillance.

Future prospects

The future of digital pest surveillance is bright as new technologies are being developed to make pest management more accurate and accessible. The use of AI, IoT, and drones can result in the automation of pest detection, monitoring, and control. Moreover, the development of models for different agro-climatic regions can lead to the customization of pest prediction, making it more accurate. The use of big data and national networks can result in a nationwide pest surveillance network, making it simpler to track pest outbreaks and trends. The farmer-level interventions such as the use of mobile apps in regional languages such as Malayalam and Hindi, along with voice-based advisory systems, can make digital pest surveillance more accessible and convenient for farmers.

Conclusion

Digital pest surveillance is a major shift from the traditional method of scouting to a smarter, quicker, and more accurate method of pest management. This can be attributed to the use of mobile apps, AI, GIS, remote sensing technologies, IoT, and cloud-based technologies for pest management. This is even more pertinent today in the wake of the challenges posed by climate change, increasing food safety concerns, and the need for the adoption of more sustainable and precision agriculture practices. Although the use of digital pest surveillance for pest management is still limited by certain factors such as connectivity barriers, digital illiteracy, high costs, and the unavailability of localized pest information, this can be addressed through the strengthening of infrastructure and further research. In the future, the use of advanced technologies and farmer-friendly innovations would make digital pest surveillance an essential tool for more resilient, eco-friendly, and precision pest management practices in agriculture.

References

Liu, C., Zhai, Z., Zhang, R., Bai, J., & Zhang, M. (2022). Field pest monitoring and forecasting system for pest control. *Frontiers in Plant Science*, 13, 990965.

IoT based intelligent pest management system for precision agriculture. (2024). *Scientific Reports*.

Silva, G., et al. (2021). Plant pest surveillance: from satellites to molecules. *Emerging Topics in Life Sciences,* 5(2), 275–287.

IoT for Real-Time Pest Detection in Agriculture. (2025). *AIIT Journal.*

AGRICULTURE BULLETIN
ISSN: 3049-2289

Biostimulants in Agriculture: A New Frontier for Soil Health and Crop Resilience

Jayashree Dey Sarkar[1], Amrita Kumar Sarkar[2], and Abhas Kumar Sinha[1]
[1]Department of Soil Science and Agricultural Chemistry, U.B.K.V., Pundibari, Coochbehar, West Bengal-736165, India
[2]Department of Agricultural Extension, Faculty of Agriculture, Guru Kashi University, Bathinda, Punjab-151302, India

Global agriculture is facing mounting challenges due to climate variability, soil degradation, and the urgent need to increase productivity while minimizing environmental impacts. In this context, biostimulants have emerged as an innovative and sustainable solution to enhance soil health, crop performance, and resilience under stress conditions. This article presents a comprehensive synthesis of biostimulants, encompassing their classification, mechanisms of action, and multifunctional roles in contemporary agricultural systems. Biostimulants are broadly categorized into microbial and non-microbial groups, including humic substances, seaweed extracts, protein hydrolysates, beneficial elements, and plant growth-promoting microorganisms. Their effects are mediated through complex physiological, biochemical, and molecular pathways, such as stimulation of root architecture, enhancement of photosynthetic efficiency, modulation of phytohormonal balance, activation of antioxidant defense systems, and optimization of plant–microbiome interactions. These processes collectively improve nutrient-use efficiency, promote crop growth and yield, and enhance tolerance to abiotic stresses, including drought, salinity, and temperature extremes. Furthermore, biostimulants contribute significantly to soil health by enhancing microbial activity, nutrient cycling, soil aggregation, and stabilization of soil organic carbon. In addition to yield improvement, biostimulants enhance crop quality and nutritional value by increasing the accumulation of vitamins, antioxidants, and bioactive compounds. However, challenges such as variability in product composition, lack of standardized application protocols, and limited field-level validation constrain their broader adoption. Future research should prioritize molecular-level investigations, development of crop-specific formulations, and integration with precision agriculture technologies. Overall, biostimulants represent a transformative approach for achieving sustainable, resilient, and climate-smart agricultural systems.

Introduction

Global agriculture is facing unprecedented challenges driven by population growth, climate variability, land degradation, and increasing pressure to reduce the environmental footprint of food production (Sarkar et al., 2023a). To meet the rising demand for food, feed, and fiber, farming systems must enhance crop productivity while simultaneously improving resource-use efficiency and safeguarding soil, water, and ecosystem health (Galindo, et al., 2025). For decades, mineral fertilizers and chemical pesticides have played a central role in sustaining yields and stabilizing production. However, their intensive and often indiscriminate use has led to a range of agronomic and environmental concerns, including soil organic matter depletion (Sarkar et al., 2023b), nutrient imbalances, reduced microbial diversity, groundwater contamination, greenhouse gas emissions, and declining nutrient-use efficiency (Suman et al., 2022). These issues threaten the long-term sustainability and resilience of agroecosystems. In response to these challenges, modern agricultural research and policy have increasingly shifted toward sustainable and regenerative production paradigms that emphasize soil health, ecological balance, and efficient use of inputs (Marcinek & Smol, 2025, Sarkar et al., 2025).Within this context, there is a growing recognition that improving crop performance cannot rely solely on increasing external inputs but must also involve enhancing the biological functioning of soils and plants. This paradigm shift has catalyzed interest in innovative, nature-based solutions that complement conventional fertilization and crop protection strategies. Plant biostimulants (PBs) have emerged as one of the most promising tools in this transition toward sustainable intensification. Unlike fertilizers, which directly supply nutrients, or pesticides, which target pests and diseases, biostimulants act primarily by stimulating natural physiological and biochemical processes in plants and soil. They enhance nutrient uptake and assimilation, improve root growth and architecture, modulate hormonal balance, and activate plant defense and stress-response pathways (Rouphael & Colla, 2020). As a result, biostimulants can improve crop growth, yield stability, and quality, even under suboptimal conditions such as drought, salinity, nutrient deficiency, and temperature extremes. Beyond their direct effects on plants, biostimulants play a critical role in improving soil health, which is increasingly recognized as the foundation of resilient and productive agroecosystems. Many biostimulant formulations derived from microbial inoculants, seaweed extracts, humic substances, protein hydrolysates, and other natural sources which enhance soil biological activity, stimulate beneficial microbial communities, and promote nutrient cycling (Li et al. 2026). These interactions contribute to improved soil structure, increased organic carbon stabilization, and enhanced availability of macro- and micronutrients, thereby creating a more favourable rhizosphere environment for crop growth. The relevance of biostimulants is further amplified under the current scenario of climate change, where crops are frequently exposed to multiple and interacting stresses. By improving plant stress tolerance and resilience, biostimulants offer a strategic means to stabilize yields while reducing reliance on high doses of synthetic inputs. This aligns closely with global sustainability goals, including climate-smart agriculture, conservation agriculture, and regenerative farming systems. Thus, biostimulants represent a new frontier in agricultural management, bridging the gap between productivity and sustainability.

2. Classification of Biostimulant

Plant biostimulants are a diverse group of inputs that differ widely in origin, composition, and mechanism of action. Based on their biological nature and functional pathways, they are broadly classified into non-microbial and microbial biostimulants. This classification provides a practical framework for understanding how different biostimulant types interact with plants and soils to enhance crop performance and agroecosystem resilience.

Non-microbial biostimulants

Non-microbial plant biostimulants comprise a wide range of organic and inorganic substances derived from natural, industrial, or recycled biological sources. Key categories include humic and fulvic substances, protein hydrolysates, amino acid formulations, seaweed and macroalgal extracts, phosphites, silicon-based products, and chitin and chitosan derivatives, among others. Despite their compositional diversity, these materials share a common function: they stimulate plant physiological and biochemical processes without acting as direct nutrient sources (López-Serrano et al., 2026)

Humic and fulvic substances, primarily derived from soil organic matter, composts are known to improve soil structure, cation exchange capacity, and nutrient availability. At the plant level, they influence root elongation, lateral root formation, and membrane permeability, thereby enhancing nutrient uptake and water-use efficiency. Protein hydrolysates and amino acid-based biostimulants, obtained through enzymatic or chemical hydrolysis of plant or animal biomass, provide readily available signaling molecules that regulate nitrogen metabolism, photosynthesis, and stress-response pathways.

ISSN: 3049-2289

Seaweed and macroalgal extracts represent one of the most widely used classes of non-microbial biostimulants. Rich in polysaccharides, betaines, phenolics, vitamins, and hormone-like compounds, these extracts modulate plant hormonal balance, promote root and shoot growth, and enhance tolerance to abiotic stresses such as drought, salinity, heavy metals and temperature extremes (Fig.1). Similarly, silicon-based products strengthen cell walls, improve mechanical resistance, and reduce biotic and abiotic stress susceptibility, while chitin and chitosan derivatives act as elicitors of plant defense responses and enhance resistance to pathogens.

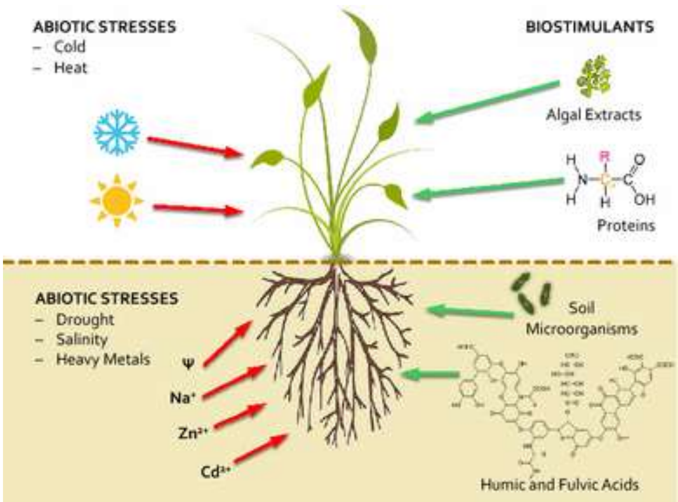


Fig. 1. The role of biostimulants as alleviator of abiotic stress in crop plants (Oosten et al., 2017)

Microbial biostimulants

Microbial biostimulants consist of living microorganisms that establish beneficial associations with plant roots or the rhizosphere (Rouphael & Colla, 2020). Major groups include arbuscular mycorrhizal fungi (AMF), plant growth-promoting rhizobacteria (PGPR). These organisms enhance plant growth through a combination of direct and indirect mechanisms that extend beyond simple nutrient supply. AMF form symbiotic relationships with plant roots, increasing the effective root surface area and facilitating the uptake of relatively immobile nutrients, particularly phosphorus and micronutrients such as zinc and copper. In addition, AMF improve soil aggregation through hyphal networks and glomalin production, thereby contributing to long-term soil structural stability and carbon sequestration. PGPR, including genera such as *Azospirillum*, *Bacillus*, and *Pseudomonas*, enhance plant growth by biological nitrogen fixation, solubilization of phosphorus and potassium, production of phytohormones (e.g., auxins and cytokinins), and suppression of soil-borne pathogens.

Toward integrated and synergistic formulations

Recent research increasingly highlights the potential of combined applications of microbial and non-microbial biostimulants. Non-microbial inputs can create a favourable biochemical and physical environment in the rhizosphere, enhancing microbial survival, colonization, and activity. In turn, microbial biostimulants can amplify the effectiveness of non-microbial compounds by improving nutrient cycling and root responsiveness. These synergistic interactions are driving the development of next generation biostimulant formulations designed to deliver more consistent and robust responses across diverse soil types, cropping systems, and environmental conditions.

3. Mechanisms of Action of Biostimulants

Biostimulants influence plant performance through a complex network of physiological, biochemical, and molecular processes that collectively enhance growth, productivity, and resilience. Unlike conventional inputs that supply nutrients directly, biostimulants act primarily as regulators and stimulators of intrinsic plant functions. Their mode of action involves multiple interconnected pathways, including root system development, photosynthetic efficiency, hormonal modulation, antioxidant defense, and plant–microbiome interactions.

Root Development and Nutrient Acquisition

One of the most widely reported effects of biostimulants is stimulation of root system development. Biostimulant components modulate

ISSN: 3049-2289

root morphology including root biomass, surface area, and lateral root formation, while also improving acquisition of nitrogen, phosphorus, iron, zinc, and other nutrients. This enhanced root architecture is particularly critical under nutrient-limited or drought conditions, where efficient resource capture determines yield stability (Kaushal et al., 2023).

Photosynthesis and Carbon Assimilation

Biostimulants significantly improve photosynthetic performance, which is central to plant growth and productivity. They enhance chlorophyll synthesis and stability, leading to increased light absorption and improved efficiency of the photosynthetic apparatus. Enhanced photosynthetic efficiency results in greater production of assimilates, which are subsequently allocated to various plant organs, supporting biomass accumulation and yield formation. Exogenous biostimulants and plant hormones have shown great promise in optimizing natural plant resilience, resulting in meaningful improvements under climate-induced stresses (Li et al., 2026)

Hormonal Regulation

Biostimulants also modulate phytohormone biosynthesis including auxins, cytokinins, gibberellins, and abscisic acid, thereby enhancing cell division, delaying senescence, and increasing tolerance to salinity, temperature extremes, and drought. Exogenous biostimulants and plant hormones have shown great promise in optimizing natural plant resilience, resulting in meaningful improvements under climate-induced stresses (Yakhin et al., 2017)

Antioxidant Defence and Stress Mitigation

Another critical mechanism involves activation of antioxidant defence systems. Biostimulants represent a promising category of environment-friendly formulations that enhance abiotic stress tolerance by modulating reactive oxygen species balance, which plays a dual role as either signalling molecules or damaging agents depending on concentration (Hasanuzzaman et al., 2021).

Molecular and Microbiome Interactions

At the molecular level, biostimulants regulate gene expression associated with nutrient transport, metabolism, and stress responses, leading to enhanced nutrient-use efficiency and overall metabolic activity. In addition to these direct effects, biostimulants modulate rhizosphere processes by altering root exudation patterns, thereby promoting the proliferation of beneficial microorganisms such as plant growth-promoting rhizobacteria and mycorrhizal fungi. This results in enhanced microbial diversity, improved nutrient cycling, and increased resistance to soil-borne pathogens. The synergistic interaction between plant systems and the soil microbiome ultimately contributes to improved plant health and long-term soil fertility (Suman et al., 2022; Galindo et al., 2025).

5. Role of Biostimulants in Agriculture

Biostimulants play a pivotal role in modern agriculture by enhancing plant performance, improving soil health, and increasing resilience to environmental stresses (Fig. 2). Their multifunctional nature allows them to influence a wide range of physiological, biochemical, and ecological processes, making them valuable tools for sustainable and climate-smart agricultural systems.

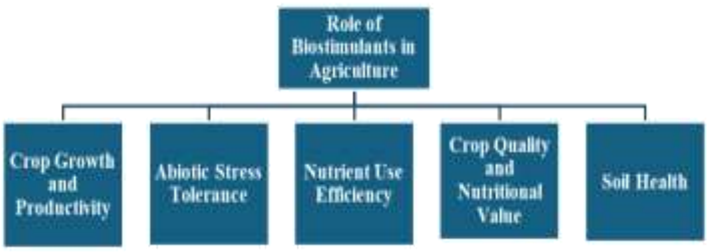


Fig. 2. Role of Biostimulant in Agriculture

Crop Growth and Productivity

Biostimulants enhance crop growth and yield by improving key physiological and developmental processes. They promote seed germination, seedling vigor, and root–shoot development, leading to efficient resource acquisition. Improved photosynthetic efficiency and nutrient utilization further contribute to higher biomass and enhanced yield attributes such as grain filling and harvest index. These benefits are largely driven by improved physiological efficiency rather than mere biomass accumulation and are particularly evident under low-input and stress-prone conditions, supporting sustainable agricultural intensification (Rouphael & Colla, 2020).

Abiotic Stress Tolerance

Biostimulants improve plant resilience to abiotic stresses such as drought, salinity, and temperature extremes through multiple coordinated mechanisms. They enhance root growth, water-use efficiency, osmotic adjustment, ion homeostasis, and antioxidant defense systems, thereby protecting cellular structures and maintaining metabolic functions. Microbial biostimulants, including AMF and PGPR, further strengthen stress tolerance by improving soil structure, water retention, and nutrient availability (Suman et al., 2022; Galindo et al., 2025).

Nutrient Use Efficiency

Biostimulants play a key role in enhancing nutrient-use efficiency (NUE) by stimulating root development, increasing nutrient transporter activity, and improving nitrogen assimilation. They also facilitate phosphorus solubilization, micronutrient mobilization, and biological nitrogen fixation. These processes reduce nutrient losses, lower fertilizer requirements, and minimize environmental impacts, thereby contributing to sustainable nutrient management (Halpern et al., 2015).

Crop Quality and Nutritional Value

Beyond yield improvement, biostimulants enhance crop quality and nutritional composition by increasing the accumulation of vitamins, minerals, antioxidants, and secondary metabolites such as phenolics and flavonoids. They also improve sensory attributes, including color, taste, and shelf life, through enhanced metabolic activity and nutrient assimilation, thereby increasing market value and consumer acceptance (Galindo et al., 2025).

Soil Health

Biostimulants significantly improve soil health by enhancing microbial diversity, nutrient cycling, and soil structure. Microbial biostimulants promote soil aggregation through hyphal networks and exudates, while non-microbial compounds improve physicochemical properties such as cation exchange capacity and organic matter stabilization. These processes enhance soil organic carbon sequestration and contribute to the development of resilient soil systems capable of sustaining long-term agricultural productivity (Marcinek & Smol, 2025).

6. Challenges and Future Prospects

Despite their significant potential, the widespread adoption of biostimulants is constrained by several challenges related to consistency, scientific understanding, and regulatory frameworks. One of the major limitations is the variability in product composition and performance, which often leads to inconsistent results across different crops and environmental conditions. Additionally, the lack of standardized application protocols regarding dosage, timing, and method of application further complicates their effective use. A limited understanding of their mechanisms of action under field conditions, as opposed to controlled environments, also restricts their broader acceptance among farmers and researchers. Regulatory ambiguities and inadequate quality control measures add to these challenges, affecting product reliability and market confidence. To overcome these limitations, future research should focus on developing a deeper molecular and omics-based understanding of biostimulant functions, enabling the design of more precise and effective formulations. Emphasis should also be placed on developing crop-specific and condition-specific biostimulants, integrating their use with precision agriculture and digital technologies, and conducting long-term field trials along with economic assessments.

ISSN: 3049-2289

7. Conclusion

Biostimulants have emerged as a promising and innovative component of sustainable agricultural systems, offering a holistic approach to enhancing crop productivity, resource-use efficiency, and environmental resilience. Unlike conventional inputs, their multifunctional nature allows them to simultaneously regulate plant physiological processes, improve nutrient dynamics, and strengthen plant tolerance to diverse abiotic stresses. Their ability to enhance soil health through improved microbial activity, nutrient cycling, and organic carbon stabilization further underscores their significance in maintaining long-term agroecosystem sustainability. In the context of increasing climate variability, soil degradation, and the need to reduce reliance on synthetic inputs, biostimulants provide a strategic pathway toward resilient and climate-smart agriculture. However, their effective adoption requires a deeper understanding of their mechanisms under field conditions, standardization of formulations and application protocols, and integration with modern precision farming technologies. Future advancements in molecular research, formulation science, and field validation will be crucial in unlocking their full potential. Overall, biostimulants represent a key frontier in bridging productivity with sustainability, contributing to the development of efficient, resilient, and environmentally sound agricultural systems capable of meeting future global food demands.

Reference

Galindo, F. S., Moreira, A., Moraes, L. A., Teixeira Filho, M. C., Jalal, A., Oliveira, C. E., ... & Pagliari, P. H. (2025). Challenges and promising opportunities for biostimulants application in sustainable agriculture. Advances in Agronomy, 193, 147-226. https://doi.org/10.1016/bs.agron.2025.05.003

Halpern, M., Bar-Tal, A., Ofek, M., Minz, D., Muller, T., & Yermiyahu, U. (2015). The use of biostimulants for enhancing nutrient uptake. Advances in agronomy, 130, 141-174. https://doi.org/10.1016/bs.agron.2014.10.001

Hasanuzzaman, M., Parvin, K., Bardhan, K., Nahar, K., Anee, T. I., Masud, A. A. C., & Fotopoulos, V. (2021). Biostimulants for the regulation of reactive oxygen species metabolism in plants under abiotic stress. Cells, 10(10), 2537. https://doi.org/10.3390/cells10102537

Kaushal, P., Ali, N., Saini, S., Pati, P. K., & Pati, A. M. (2023). Physiological and molecular insight of microbial biostimulants for sustainable agriculture. Frontiers in Plant Science, 14, 1041413. https://doi.org/10.3389/fpls.2023.1041413

Li, J., Forghieri, G., Geelen, D., Du Jardin, P., & Brown, P. H. (2026). The optimization of crop response to climatic stress through modulation of plant stress response mechanisms. Opportunities for biostimulants and plant hormones to meet climate challenges. New Phytologist, 249(1), 130-151. https://doi.org/10.1111/nph.70701

López-Serrano, L., Scalschi, L., Simeón, R., San Bautista, A., & González-Hernández, A. I. (2026). Harnessing the Power of Biostimulants: A Comprehensive Review of Their Role in Enhancing Agricultural Productivity and Sustainability. Applied Sciences, 16(4), 1924. https://doi.org/10.3390/app16041924

Marcinek, P., & Smol, M. (2025). Barriers and Drivers of Using Alternative Fertilizers in Sustainable Agriculture: Case Study of Poland. Environmental Management, 75(12), 3188-3202. https://doi.org/10.1007/s00267-025-02259-2

Van Oosten, M. J., Pepe, O., De Pascale, S., Silletti, S., & Maggio, A. (2017). The role of biostimulants and bioeffectors as alleviators of abiotic stress in crop plants. Chemical and Biological Technologies in Agriculture, 4(1). https://doi.org/10.1186/s40538-017-0089-5

Rouphael, Y., & Colla, G. (2020). Biostimulants in agriculture. Frontiers in plant science, 11, 40. https://doi.org/10.3389/fpls.2020.00040

Sarkar, J.D., Sarkar, A.K., & Lal, S.P. (2023a). A Critical Review of Vermi-Composting in Urban and Peri-Urban Waste Management Apropos Robust Environment. Journal of Agricultural Extension Management, 24(2), 53-62. https://www.manage.gov.in/publications/journal/jul-dec2023.pdf#page=61

Sarkar, J.D., Sarkar, A.K., & Mondal, P. (2023b). Sustainable Manipulation of Agricultural Residues in Bioenergy Production. In: Rakshit, A., Biswas, A., Sarkar, D., Meena, V.S., Datta, R. (eds) Handbook of Energy Management in Agriculture in Agriculture in Agriculture. Springer, Singapore. https://doi.org/10.1007/978-981-19-7736-7_36-1

Sarkar, J.D., Sarkar, A.K., Gupta S. & Rai, S. (2025). Regenerative agriculture: a paradigm shift in sustainable farming practices. Agri Articles, 5(1). ISSN: 2582-9882

Suman, J., Rakshit, A., Ogireddy, S. D., Singh, S., Gupta, C., & Chandrakala, J. (2022). Microbiome as a key player in sustainable agriculture and human health. Frontiers in Soil Science, 2, 821589. https://doi.org/10.3389/fsoil.2022.821589

Yakhin, O. I., Lubyanov, A. A., Yakhin, I. A., & Brown, P. H. (2017). Biostimulants in plant science: a global perspective. Frontiers in plant science, 7, 2049. https://doi.org/10.3389/fpls.2016.02049

AGRICULTURE BULLETIN
ISSN: 3049-2289

Stay-Green Trait: A Key Strategy for Improving Yield and Stress Tolerance in Crops

B. Sriram Kumar* and K. Alekya[1]
*Ph.D. Genetics and Plant Breeding, Acharya N.G. Ranga Agriculture university, Andhra Pradesh
[1]Ph.D. Genetics and Plant Breeding, Acharya N.G. Ranga Agriculture university, Andhra Pradesh

Stay-green trait has gained importance as a key physiological characteristic that enhances plant resilience. This trait enables crops to retain green leaf area and sustain photosynthetic activity beyond flowering, thereby supporting prolonged grain filling and improved yield under stress environments. Stay-green expression may be functional, where photosynthesis is maintained, or non-functional, where greenness persists without effective carbon assimilation. The trait is governed by multiple genes and quantitative trait loci (QTLs), many of which have been identified in crops such as sorghum, wheat, rice, and maize. These genetic factors provide opportunities for targeted improvement through modern breeding approaches, including marker-assisted selection. Despite its advantages, extended leaf longevity may sometimes limit nutrient translocation to developing seeds, highlighting the need for careful trait integration. Overall, the stay-green trait represents a valuable component in developing climate-resilient crop varieties also and ensuring sustainable agricultural production under stress-prone conditions.

Introduction

Increasing global population and climate change are posing serious threats to crop productivity. Among various environmental stresses, drought and heat stress are the most damaging factors affecting crop yield and biomass production. To address these challenges, plant breeders are focusing on traits that enhance crop resilience and yield stability under stress conditions. One such important trait is the stay-green (SG) trait, which allows plants to maintain green leaves and photosynthetic activity for a longer period after flowering. This extended photosynthetic activity supports longer grain filling duration and ultimately leads to higher yields. The stay-green trait refers to the ability of plants to delay leaf senescence (aging) and maintain green foliage during the grain filling stage. Plants with this trait retain chlorophyll longer, allowing continued photosynthesis even under stressful conditions such as drought and high temperatures. There are two types of stay green traits; a) Functional stay-green in which leaves remain green and maintain photosynthetic capacity, highly useful in crop breeding and b) non-functional stay-green in which leaves remain green but photosynthesis declines, less beneficial for yield. These types are considered more valuable for improving crop productivity under stress conditions. Conversely, delayed senescence, or "stay-green" traits, though beneficial in extending photosynthetic activity, can sometimes interfere with nutrient remobilization needed for seed development. Balancing these factors to optimize both yield and quality under various environmental stresses remains a critical and ongoing challenge for crop scientists and geneticists.

Importance in Crop Improvement

The stay-green trait is associated with several beneficial physiological and agronomic characteristics. It contributes to improved crop performance through multiple mechanisms.

Table 1: Major Benefits of Stay-Green Trait

Characteristic	Effect on Crop Performance
Extended photosynthesis	More carbohydrate

	production
Delayed senescence	Longer grain filling duration
Improved water use efficiency	Better drought tolerance
Enhanced nitrogen utilization	Improved biomass and yield
Increased grain number per ear	Higher productivity

Stay-Green in Major Crops

The stay-green trait has been studied in several important crops.

Table 2: Stay-Green Research in Major Crops

Crop	Major findings
Sorghum	One of the best-studied crops for stay-green; several QTLs identified for drought tolerance
Wheat	Stay-green linked with heat tolerance and improved grain filling
Rice	Genetic mutations controlling chlorophyll degradation affect stay-green expression
Maize	Associated with improved photosynthesis and delayed leaf senescence
Barley	Limited research but linked to drought tolerance and grain filling stability
Cucumber	Studied the genetic basis of low-temperature (LT) tolerance in cucumbers using genome-wide association approach
Tomato	Stay green linked with inhibiting chlorophyll degradation

These studies indicate that the stay-green trait plays a crucial role in improving crop adaptation to stressful environments.

Genetic Control of Stay-Green

Stay-green is a quantitative trait controlled by multiple genes or quantitative trait loci (QTLs). Several QTLs responsible for stay-green have been identified in major crops.

Table 3: Examples of Stay-Green QTLs

Crop	Important qtls
Sorghum	Stg1, Stg2, Stg3 and Stg4
Wheat	QTLs on chromosomes 1A, 3B, 7D
Rice	Csfl6, Tcs9 and others
Maize	Multiple QTLs associated with chlorophyll retention
Barley	QTLs identified on chromosome 5H
Cucumber	a specific genetic variation (SNP) within the STAYGREEN(CsSGR) gene, located at the gLTT5.1locus, was identified as being linked to LT tolerance.
Tomato	Research has identified that mutations in the STAY-GREEN 1 (SGR1)gene inhibit chlorophyll degradation during tomato fruit ripening.

These QTLs can be incorporated into breeding programs through marker-assisted selection (MAS) to develop stress-tolerant varieties.

ISSN: 3049-2289

Role in Climate-Resilient Agriculture

The stay-green trait is particularly valuable for improving crop performance under terminal drought stress, which occurs during the grain filling stage. Stay-green plants maintain photosynthesis longer, ensuring sufficient assimilates for grain development. With the increasing occurrence of drought and heat stress due to climate change, incorporating stay-green traits into breeding programs is becoming an essential strategy for achieving sustainable food production.

Conclusion

The stay-green trait is an important physiological and genetic characteristic that enhances yield stability and stress tolerance in crops. By maintaining photosynthetic activity during grain filling, stay-green plants can produce higher yields even under unfavorable environmental conditions. Future research should focus on identifying additional genes controlling this trait, understanding its physiological mechanisms, and integrating it into crop breeding programs. Combining stay-green with other beneficial traits could significantly contribute to developing climate-resilient varieties and ensuring global food security.

REFERENCES

Kamal, N.M., Gorafi, Y.S.A., Abdelrahman, M., Abdellatef, E and Tsujimoto, H. 2019.

Stay-Green Trait: A Prospective Approach for Yield Potential, and Drought and Heat Stress Adaptation in Globally Important Cereals. *International journal of molecular sciences.* 20: 5837. doi:10.3390/ijms20235837.

Yasaswini, Chetariya, C. P and Delvadiya. 2025. Maximizing Crop Resilience: Exploring Stay-Green Traits for Sustainable Agriculture and Crop Research. *International Journal of Plant & Soil Science*. 37(3): 227-246.

AGRICULTURE BULLETIN

ISSN: 3049-2289

Biochar for Carbon Sequestration and Climate Change Mitigation in Agricultural Soils

Vaibhav Shivaji Chakor, Atharva Laxman More, and Rishikesh Shivprasad Patil

M.Sc. (Agriculture) Soil Science, Research Executive, Center of Excellence (CoE), Urban Farms Co., India

M.Sc. (Agriculture) Soil Science, R&D Operation Associate, Division of Biochar Fertilizer and R&D, MASH MAKES, India

B.Sc. (Hons.) Agriculture, Senior Soil Analyst, Division of Biochar Fertilizer and R&D, MASH MAKES, India

Biochar, a stable carbon-rich material produced by pyrolysis of organic biomass under limited oxygen conditions, has emerged as a promising strategy for carbon sequestration and climate change mitigation within agricultural soils. Its unique physicochemical properties enable long-term carbon storage, improve soil health, and influence greenhouse gas (GHG) emissions dynamics. This comprehensive review explores the mechanisms, benefits, challenges, and future prospects of biochar application in agricultural soils for carbon sequestration and climate mitigation. It integrates current scientific understanding of biochar production, soil interactions, carbon stability, and impacts on soil biogeochemical cycles, with an emphasis on practical implementation and environmental outcomes.

1.Introduction

Anthropogenic greenhouse gas emissions, primarily carbon dioxide (CO_2), have accelerated climate change, threatening global ecosystems and food security. Agricultural soils serve as both sources and sinks of carbon, presenting opportunities for climate mitigation through improved land management. Biochar application to soils has gained attention as a carbon-negative technology capable of sequestering atmospheric carbon in a chemically stable form while simultaneously enhancing soil quality and productivity.

Biochar's climate mitigation potential arises from its long-term carbon storage capacity, ability to reduce emissions of potent greenhouse gases such as nitrous oxide (N_2O) and methane (CH_4), and its role in improving soil resilience against environmental stresses. This review synthesizes current knowledge on biochar’s role in carbon sequestration and climate mitigation within agricultural systems, focusing on production methods, carbon stability, soil interactions, greenhouse gas dynamics, and implementation challenges.

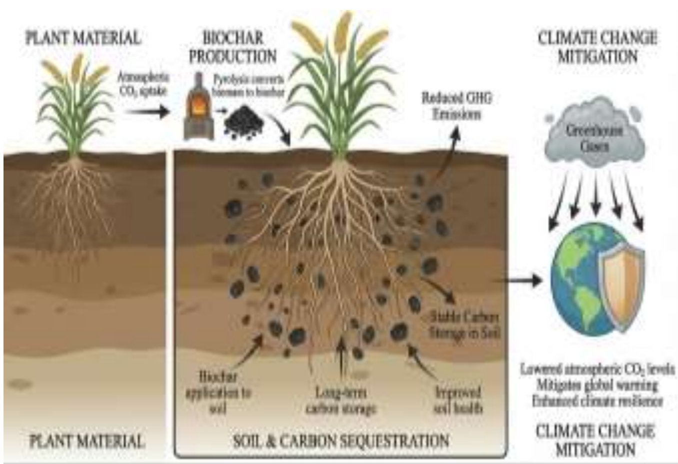


Figure 1: Biochar for Carbon Sequestration and Climate Change Mitigation in Agricultural Soils

2. Biochar Production and Characteristics Relevant to Carbon Sequestration

2.1 Feedstock Selection

The selection of biomass feedstock critically influences biochar properties and its carbon sequestration potential. Common feedstocks include agricultural residues (e.g., crop stover, husks), forestry residues (e.g., wood chips, sawdust), and organic wastes (e.g., manure, biosolids). Woody

ISSN: 3049-2289

biomass typically produces biochars with higher aromatic carbon content and enhanced chemical stability, whereas herbaceous and manure-based feedstocks often yield biochars richer in nutrients but with comparatively lower recalcitrance. Feedstock sustainability and availability are essential considerations for large-scale biochar production.

Feedstock characteristics such as lignin, cellulose, and hemicellulose content influence the resultant biochar properties. For example, lignin-rich feedstocks tend to produce biochars with higher aromaticity and greater chemical stability. The moisture content and elemental composition of feedstocks also affect pyrolysis efficiency and biochar yield.

2.2 Pyrolysis Process Parameters

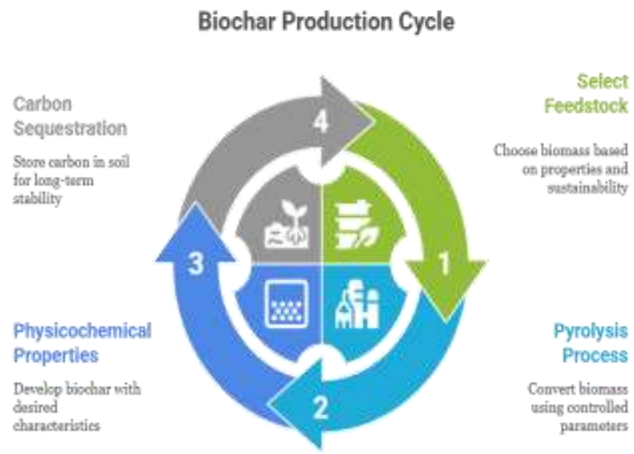
Pyrolysis parameters such as temperature, heating rate, and residence time determine the physicochemical properties of biochar. Higher pyrolysis temperatures (>500°C) favor the formation of condensed aromatic carbon structures, increasing chemical recalcitrance and stability. Slow pyrolysis generally produces biochars with higher carbon yields and surface areas compared to fast pyrolysis. Optimizing these parameters is critical to maximizing both carbon stability and agronomic benefits.

The pyrolysis atmosphere (e.g., oxygen-limited, inert gas) and reactor design also influence biochar characteristics. For instance, gasification processes operate at higher temperatures and produce biochars with lower yields but higher stability. Understanding these process variables allows tailoring biochar properties for specific soil and environmental applications.

2.3 Physicochemical Properties

Biochar exhibits a porous structure and high surface area, which enhance soil aeration and water retention. Its alkaline pH can ameliorate acidic soils, while functional groups such as carboxyl and hydroxyl contribute to cation exchange capacity (CEC), improving nutrient retention. The aromatic carbon rings confer resistance to microbial degradation and chemical oxidation, key for long-term carbon sequestration. Mineral ash content supplies essential nutrients and buffers soil pH.

Biochar's surface chemistry, including the presence of oxygen-containing functional groups, influences its interaction with soil nutrients and microbes. High surface area and porosity provide adsorption sites for nutrients and water, improving soil fertility and moisture dynamics. The pH effect of biochar varies with feedstock and pyrolysis conditions, typically ranging from neutral to alkaline, which can ameliorate acidic soils but may be detrimental in already alkaline soils.



3. Mechanisms of Carbon Sequestration by Biochar in Soils

3.1 Chemical Stability

Biochar's condensed aromatic carbon structures are highly resistant to microbial enzymatic degradation and abiotic oxidation, resulting in slow decomposition rates. Analytical techniques such as nuclear magnetic resonance (NMR) spectroscopy confirm the dominance of stable aromatic carbon fractions in biochar, correlating with long soil residence times often spanning decades to millennia.

The degree of aromaticity, molecular structure, and presence of condensed polyaromatic rings determine biochar's recalcitrance. These structures resist enzymatic breakdown and chemical oxidation,

ISSN: 3049-2289

making biochar a persistent form of soil carbon. The chemical stability is enhanced by high pyrolysis temperatures, which promote the formation of these condensed structures.

3.2 Physical Protection

The porous matrix of biochar physically shields carbon by adsorbing organic molecules and providing microhabitats inaccessible to decomposers. Biochar also enhances soil aggregation, encapsulating organic matter and reducing its mineralization by microbes, thereby further stabilizing carbon in soil.

Physical protection occurs as biochar particles adsorb native soil organic matter and microbial exudates, creating organo-mineral complexes. These complexes reduce microbial access to carbon substrates, slowing decomposition. Biochar's role in improving soil structure promotes aggregate formation, which physically protects organic carbon within soil microaggregates.

3.3 Soil Mineral Interactions

Biochar interacts with soil minerals to form organo-mineral complexes, which stabilize carbon by reducing its bioavailability to microbes. These complexes slow biochar decomposition and enhance carbon retention within the soil matrix.

Mineral surfaces such as clays and metal oxides adsorb biochar particles and associated organic matter, creating stable complexes that resist microbial degradation. These interactions are influenced by soil mineralogy, biochar surface chemistry, and environmental conditions.

3.4 Environmental Influences

Soil texture, moisture, temperature, pH, and microbial community composition significantly affect biochar persistence. Biochar generally exhibits greater stability in acidic, sandy soils with low microbial activity. Climatic factors such as temperature and precipitation modulate decomposition rates, influencing overall carbon sequestration efficacy.

In wetter or warmer climates, increased microbial activity may accelerate biochar decomposition, although the recalcitrance of biochar still confers longer persistence compared to native organic matter. Soil pH influences microbial community composition and activity, affecting biochar turnover. Management practices such as tillage can also impact biochar stability by altering soil structure and microbial dynamics.

4. Impacts of Biochar on Soil Carbon Dynamics and Greenhouse Gas Emissions

4.1 Soil Organic Carbon Pools

Biochar addition increases total soil organic carbon (SOC) by directly contributing stable carbon and by stimulating native SOC accumulation through priming effects. Positive priming accelerates microbial turnover of native SOC, whereas negative priming slows decomposition. The net effect depends on biochar properties, soil type, and environmental conditions.

Biochar can enhance SOC by providing a substrate for microbial colonization and by improving soil conditions favorable for organic matter stabilization. However, priming effects are complex and context-dependent; some studies report increased native SOC mineralization following biochar addition, while others observe stabilization.

4.2 Nitrous Oxide Emissions

Biochar application frequently reduces N_2O emissions by improving soil aeration, increasing pH, altering microbial community structure, and enhancing nitrogen retention. These changes limit denitrification and nitrification processes responsible for N_2O production, a greenhouse gas with a global warming potential approximately 298 times that of CO_2 over 100 years.

The porous structure of biochar enhances soil oxygen diffusion, reducing anaerobic microsites where

ISSN: 3049-2289

denitrification occurs. Elevated pH alters microbial enzymatic activity, favoring complete reduction of N_2O to N_2. Biochar's nutrient retention reduces nitrate leaching and substrate availability for nitrifiers and denitrifiers, further mitigating emissions.

4.3 Methane Emissions

In flooded or anaerobic soils such as rice paddies, biochar can suppress methane emissions by improving soil aeration, stimulating methanotrophic bacteria, and altering redox conditions. However, the magnitude and direction of effects vary depending on soil type and biochar characteristics.

Biochar enhances oxygen availability in the rhizosphere, promoting methane oxidation by methanotrophs. Changes in soil redox potential and microbial community composition modulate methane production and consumption. Some biochars may also adsorb methane precursors or intermediates, influencing emissions.

4.4 Carbon Dioxide Emissions

Biochar's direct CO_2 emissions from decomposition are minimal relative to labile organic matter. Nonetheless, indirect effects via priming and soil respiration responses must be considered to accurately assess net carbon balance.

Priming effects may increase or decrease CO_2 emissions by stimulating or suppressing microbial mineralization of native SOC. Biochar-induced changes in soil moisture and temperature can also influence soil respiration rates. Comprehensive assessments require long-term monitoring.

Table 1: Biochar-Mediated Climate Change Mitigation in Agricultural Systems

Mitigation Pathway	Mechanism	Observed Effects	Quantitative Impact (Reported Range)	Environmental Benefit
Carbon Sequestration	Stable carbon storage in soil	Long-term C sink	0.5–3.0 t C ha^{-1} yr^{-1}	Reduced atmospheric CO_2
Reduction in N_2O Emissions	Improved aeration and altered N cycling	Lower denitrification rates	10–80% reduction	Lower GHG intensity
Reduction in CH_4 Emissions	Enhanced soil aeration	Suppression of methanogenesis	5–50% reduction	Mitigation of methane emissions
Improved Nitrogen Use Efficiency (NUE)	Nutrient retention and slow release	Reduced fertilizer losses	10–30% increase in NUE	Indirect emission reduction
Soil Moisture Retention	Porous structure enhances water holding	Reduced drought stress	15–40% increase in water retention	Climate resilience
Soil Fertility Enhancement	Improved nutrient availability and	Increased crop productivity	10–25% yield increase	Sustainable production

	microbial activity			
Waste Biomass Utilization	Conversion of residues into biochar	Reduced open burning	Significant reduction in CO_2 emissions	Circular economy support
Energy Co-benefits	Biochar production generates syngas/bio-oil	Renewable energy source	Variable	Reduces fossil fuel dependence

5. Agronomic and Environmental Benefits of Biochar Application

5.1 Soil Fertility Improvement

Biochar enhances nutrient retention by increasing soil cation exchange capacity and reducing nutrient leaching. The mineral ash fraction supplies essential nutrients, improving soil fertility. Enhanced nutrient availability supports plant growth, increasing biomass and organic carbon input to soils.

Biochar can adsorb and slowly release nutrients such as ammonium, nitrate, and phosphate, improving nutrient use efficiency. This reduces fertilizer requirements and associated environmental impacts. The liming effect of biochar ameliorates acidic soils, enhancing nutrient availability.

5.2 Water Retention and Soil Structure

The porous nature of biochar improves soil water holding capacity, infiltration, and aggregation, enhancing drought resilience and reducing erosion. These physical improvements indirectly contribute to carbon sequestration by promoting plant productivity and soil organic matter accumulation.

Improved soil structure facilitates root growth and microbial habitat, supporting nutrient cycling and plant health. Enhanced water retention buffers plants against moisture stress, stabilizing yields under variable climatic conditions.

5.3 Soil Microbial Community Modulation

Biochar influences soil microbial diversity and activity, favoring beneficial populations involved in nutrient cycling and carbon stabilization. Enhanced microbial biomass and enzymatic activity support soil health and carbon turnover dynamics.

Biochar provides refuge for microbes, stabilizes microbial communities, and can shift microbial functional groups towards those promoting nutrient availability and organic matter stabilization. These changes contribute to improved soil ecosystem functioning.

6. Challenges and Limitations in Biochar-Based Carbon Sequestration

6.1 Variability and Standardization

Heterogeneity in biochar feedstocks and production methods leads to variable properties and inconsistent effects on soils and carbon sequestration. Lack of standardized production protocols and quality control complicate comparisons, assessment, and scaling efforts.

Developing standardized definitions, characterization methods, and quality benchmarks is essential to ensure reproducibility and regulatory acceptance.

6.2 Measurement and Monitoring

Quantifying biochar carbon stability and sequestration at field scales is challenging due to methodological limitations in tracing biochar-derived carbon and distinguishing it from native SOC. Long-term monitoring is required to validate sequestration claims.

Isotopic labeling, molecular markers, and spectroscopic techniques offer potential solutions but require further development and validation.

6.3 Economic and Logistical Constraints

Costs associated with biochar production, transportation, and application may limit adoption, particularly among smallholder farmers. Feedstock availability and pyrolysis infrastructure are critical factors influencing feasibility.

Scale-up requires economic incentives, cost reductions through technological innovation, and integration with existing agricultural practices.

6.4 Potential Negative Effects

Excessive biochar application or inappropriate biochar types may unfavorably alter soil pH, immobilize nutrients, or disrupt native microbial communities. Site-specific assessments are essential to avoid adverse outcomes.

Understanding biochar-soil interactions in diverse environments is critical to optimize application rates and prevent negative impacts.

7. Strategies to Optimize Biochar for Carbon Sequestration

7.1 Feedstock and Pyrolysis Optimization

Selecting feedstocks rich in lignin and cellulose and optimizing pyrolysis conditions to maximize aromatic carbon formation enhance biochar stability and carbon sequestration potential.

Tailoring biochar properties to specific soil and crop requirements can maximize benefits.

7.2 Tailored Biochar Amendments

Designing biochars with specific physical and chemical properties adapted to soil types and cropping systems can improve carbon retention and agronomic benefits.

Functionalization or modification of biochar surfaces may enhance nutrient retention or microbial interactions.

7.3 Integration with Other Soil Management Practices

Combining biochar application with organic amendments, cover cropping, reduced tillage, and nutrient management can synergistically enhance soil carbon sequestration.

Holistic soil health management maximizes carbon storage and agricultural productivity.

7.4 Enhancing Microbial Interactions

Inoculating biochar with beneficial microbes or integrating biochar with biofertilizers can improve microbial colonization and nutrient cycling, supporting carbon stabilization.

Microbial inoculants may enhance biochar's effects on soil processes and plant growth.

8. Policy and Climate Mitigation Frameworks

8.1 Inclusion in Carbon Markets

Recognition of biochar-based carbon sequestration in carbon credit schemes can incentivize adoption by providing financial returns for farmers and land managers.

Clear methodologies for quantifying and verifying biochar carbon credits are needed.

8.2 Regulatory and Certification Standards

Developing guidelines for biochar production, quality, and application ensures environmental safety and efficacy, facilitating market development.

Standards promote trust and acceptance among stakeholders.

8.3 Research and Extension Support

Investment in research, demonstration projects, and farmer education is critical to promote best practices and widespread adoption.

ISSN: 3049-2289

Collaborative efforts among academia, industry, and policymakers enhance knowledge transfer.

9. Future Research Directions

1. Long-term, multi-site field trials across diverse agroecosystems to quantify biochar carbon sequestration and greenhouse gas mitigation.
2. Development of robust analytical methods to trace biochar carbon and assess stability in soils.
3. Exploration of biochar interactions with soil microbial communities and their role in carbon dynamics.
4. Economic analyses and life cycle assessments to evaluate sustainability and scalability.
5. Integration of biochar application with emerging climate-smart agriculture technologies.

10. Conclusion

Biochar application to agricultural soils offers a multifaceted approach to climate change mitigation by enabling long-term carbon sequestration, reducing greenhouse gas emissions, and improving soil health and productivity. Despite challenges related to variability, measurement, and economics, ongoing research and technological advances hold promise for optimizing biochar use as a sustainable soil amendment. Integrating biochar within holistic land management and climate mitigation frameworks can contribute significantly to global efforts in reducing atmospheric CO_2 concentrations and enhancing agricultural resilience in a changing climate.

References

Lorenz, K., & Lal, R. (2014). Biochar application to soil for climate change mitigation by soil organic carbon sequestration. *Journal of plant nutrition and soil science*, *177*(5), 651-670.

Gupta, D. K., Gupta, C. K., Dubey, R., Fagodiya, R. K., Sharma, G., A, K., ... & Shukla, A. K. (2020). Role of biochar in carbon sequestration and greenhouse gas mitigation. In *Biochar applications in agriculture and environment management* (pp. 141-165). Cham: Springer International Publishing.

Yadav, R. K., Yadav, M. R., Kumar, R., Parihar, C. M., Yadav, N., Bajiya, R., ... & Yadav, B. (2017). Role of biochar in mitigation of climate change through carbon sequestration. *Int J Curr Microbiol App Sci*, *6*(4), 859-866.

Lehmann, J., Cowie, A., Masiello, C. A., Kammann, C., Woolf, D., Amonette, J. E., ... & Whitman, T. (2021). Biochar in climate change mitigation. *Nature Geoscience*, *14*(12), 883-892.

Lal, R. (2004). Soil carbon sequestration to mitigate climate change. *Geoderma*, *123*(1-2), 1-22.

Vetter, S. H., Abdalla, M., Kuhnert, M., & Smith, P. (2022). Soil carbon sequestration and biochar.

AGRICULTURE BULLETIN
ISSN: 3049-2289

Digital Extension Services: Transforming Agricultural Knowledge Dissemination through ICT Tools

Sumesh Sharma*, Manmeet Kaur and Nikhil Thakur
Research Scholar, Department of Agricultural Extension and Communication, College of Agriculture, Swami Keshwanand Rajasthan Agricultural University, Bikaner, Rajasthan, India
Assistant Professor, Department of Agricultural Extension and Communication, College of Agriculture, Swami Keshwanand Rajasthan Agricultural University, Bikaner, Rajasthan, India
Research Scholar, Department of Social Science, College of Forestry, Dr. Yashwant Singh Parmar University of Horticulture and Forestry

Agricultural extension services play a crucial role in transferring knowledge, innovations, and technologies from research institutions to farmers. However, traditional extension systems often face challenges such as limited manpower, delayed information delivery, and difficulties in reaching remote farming communities. The rapid advancement of Information and Communication Technologies (ICTs) has created new opportunities to overcome these limitations and enhance the efficiency of agricultural knowledge dissemination. Digital extension services utilize various ICT tools such as mobile phones, mobile applications, web portals, social media platforms, interactive voice response systems, and remote sensing technologies to deliver timely and location-specific agricultural information to farmers. These digital platforms enable farmers to access real-time advisories on weather conditions, pest and disease management, crop production practices, and market price information. Digital extension services also facilitate interactive communication between farmers, researchers, and extension professionals, thereby improving decision-making and promoting the adoption of improved agricultural practices. Despite their numerous benefits, challenges such as limited digital infrastructure, low digital literacy, and language barriers still hinder the widespread adoption of digital extension systems in rural areas. Strengthening digital infrastructure, improving farmer training, and developing user-friendly applications in local languages can enhance the effectiveness of these services. Overall, digital extension services have the potential to transform agricultural advisory systems and contribute significantly to sustainable agricultural development and food security.

1.Introduction

Agriculture is a knowledge-intensive sector where timely and accurate information is essential for improving productivity, profitability, and sustainability. Farmers rely on diverse sources of knowledge to make decisions related to crop selection, soil fertility, irrigation, pest and disease management, and marketing. Traditionally, agricultural information has been disseminated through extension systems involving field visits, training programs, demonstrations, and printed materials. These conventional approaches have played a significant role in transferring scientific knowledge to farmers and supporting agricultural development.

However, traditional extension systems face several limitations in the modern context. A major challenge is the inadequate ratio of extension workers to farmers, especially in developing countries, where one officer often serves thousands of farmers. Additionally, geographical constraints such as remote locations and poor infrastructure hinder effective communication, leading to delayed or insufficient advisory services.

The emergence of Information and Communication Technologies (ICTs) has transformed agricultural extension by addressing these limitations. Tools such as mobile phones, internet platforms, mobile applications, remote sensing, and social media enable rapid, wide-scale, and interactive dissemination of information. Digital extension services integrate these technologies with conventional methods to provide real-time, location-specific advisories on weather, crop management, pest control, market prices, and government schemes.

The increasing penetration of smartphones, improved rural connectivity, and growing digital literacy have accelerated the adoption of digital extension services, particularly in developing countries. Governments, research institutions, and private organizations are actively promoting digital agriculture initiatives to enhance knowledge delivery. Overall, digital extension services represent a powerful approach to improving decision-making, increasing efficiency, and supporting sustainable agricultural development.

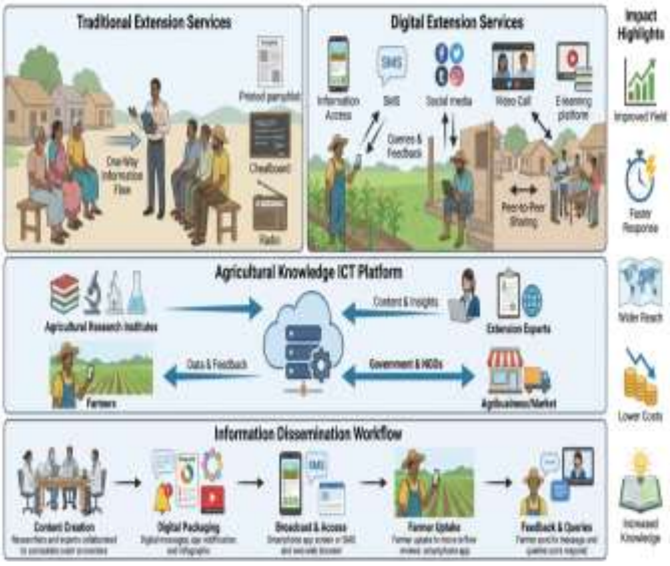


Figure 1: Digital Extension Services

2. Evolution of Agricultural Extension in the Digital Era

Agricultural extension systems have evolved significantly over the past century in response to technological advancements and changing agricultural needs. Initially, extension services were primarily based on direct interpersonal communication between extension agents and farmers. Extension workers visited farms, conducted field demonstrations, organized training programs, and provided advice on improved agricultural practices. These methods allowed farmers to observe new technologies directly and interact with experts. While traditional extension methods proved effective in many cases, their impact was often limited by logistical and financial constraints. The number of farmers that extension workers could reach was restricted by time, distance, and available resources. As agricultural production expanded and farming communities grew, the need for more efficient communication channels became evident. The introduction of mass communication media, such as radio and television, marked the first major technological shift in agricultural extension. Agricultural programs broadcast through radio stations and television networks helped reach large audiences of farmers simultaneously. These programs provided valuable information about crop production techniques, pest management strategies, and government agricultural policies. However, these communication channels were largely one-directional, meaning farmers could receive information but had limited opportunities to ask questions or provide feedback. The digital revolution of the 21st century has transformed the extension landscape even further. The widespread availability of mobile phones, internet connectivity, and digital communication platforms has enabled the development of interactive and personalized extension services. Farmers can now access agricultural information anytime and anywhere using their mobile devices. Modern digital extension systems often follow a hybrid approach, combining traditional extension methods with ICT tools. Extension agents continue to provide field-level support, while digital technologies enhance the speed and efficiency of information dissemination. For example, extension workers may use mobile apps to send advisories to farmers, monitor crop conditions, or collect data from the field. This integration of digital technologies into extension systems has greatly expanded the reach and effectiveness of

ISSN: 3049-2289

agricultural advisory services. Farmers can now connect directly with agricultural experts, participate in online training sessions, and share experiences with fellow farmers through digital platforms.

3. ICT Tools Used in Digital Agricultural Extension

Various ICT tools are currently being used to support digital extension services and improve agricultural knowledge dissemination. These technologies facilitate rapid communication, enhance farmer participation, and provide data-driven recommendations.

3.1 Mobile Phones and SMS Advisory Services

Mobile phones are one of the most widely used ICT tools in agriculture. In many rural areas, even farmers who lack access to computers or internet services possess basic mobile phones. SMS-based advisory services deliver short messages containing essential agricultural information, such as weather forecasts, pest outbreak alerts, fertilizer recommendations, and market price updates. These messages provide farmers with timely guidance that can help them take preventive measures and optimize their farm operations. SMS services are particularly valuable during critical agricultural stages such as sowing, irrigation scheduling, and pest management.

3.2 Mobile Applications

Agricultural mobile applications have become increasingly popular as smartphone usage grows in rural areas. These applications offer a wide range of services, including crop advisory, soil health monitoring, fertilizer recommendations, pest and disease diagnosis, and market information. Some advanced applications incorporate image recognition technology, enabling farmers to upload photographs of diseased plants. Experts or automated systems analyze these images and recommend appropriate solutions. Mobile apps also provide location-specific recommendations based on local climate conditions and soil characteristics.

3.3 Internet and Web-Based Platforms

Web-based platforms and agricultural portals serve as comprehensive knowledge repositories for farmers and extension workers. These platforms provide access to research publications, technical guidelines, training modules, weather forecasts, and market information. Online learning platforms also allow farmers to participate in virtual training programs, webinars, and digital workshops that improve their knowledge and skills.

3.4 Social Media Platforms

Social media platforms such as WhatsApp, Facebook, YouTube, and Telegram have become important channels for agricultural communication. Farmers use these platforms to form online communities where they share experiences, post photographs of crop problems, and discuss farming practices. Agricultural experts and extension organizations use social media to disseminate educational videos, demonstrations, and success stories that encourage the adoption of improved agricultural technologies.

Table 1: Types of Digital Extension Tools and Their Functions

Tool Category	ICT Tool	Function	Key Advantage	Limitation
Mobile-Based	SMS, Mobile Apps	Dissemination of advisories, alerts	Wide reach, real-time updates	Requires mobile literacy
Internet-Based	Web portals, e-learning platforms	Knowledge sharing, training	Access to large databases	Internet dependency

Social Media	WhatsApp, YouTube, Facebook	Farmer interaction, awareness	Rapid communication	Misinformation risk
Remote Sensing & GIS	Satellite data, GPS tools	Crop monitoring, advisory	Precision-based decisions	Technical complexity
AI-Based Systems	Chatbots, decision tools	Personalized recommendations	High accuracy	Cost & data requirement

3.5 Interactive Voice Response Systems

Interactive Voice Response (IVR) systems enable farmers to obtain agricultural information through voice-based communication. Farmers can call a toll-free number and listen to recorded messages in their local language or connect directly with agricultural experts. This technology is particularly beneficial for farmers with limited literacy levels, as it allows them to receive information through audio communication.

3.6 Remote Sensing and Geographic Information Systems

Remote sensing technologies and Geographic Information Systems (GIS) provide valuable data about crop health, soil moisture levels, and environmental conditions. Satellite imagery helps identify crop stress, drought conditions, pest outbreaks, and nutrient deficiencies. These technologies allow extension services to provide location-specific advisory services, enabling farmers to take appropriate actions based on field conditions.

4. Role of Digital Extension in Agricultural Knowledge Dissemination

Digital extension services play a crucial role in improving the efficiency and effectiveness of agricultural knowledge dissemination. One of the key advantages of digital platforms is their ability to deliver information quickly and efficiently. Farmers can receive real-time updates about weather forecasts, pest outbreaks, and market prices through digital communication channels. This allows them to take timely actions that reduce risks and improve productivity. Digital platforms also facilitate two-way communication between farmers and agricultural experts. Farmers can send queries, upload images of crop problems, and receive expert advice within a short time. This interactive communication improves problem-solving and enhances farmer confidence. Digital extension also supports climate-smart agriculture, which is essential in the face of increasing climate variability. Weather-based advisory systems help farmers adjust planting schedules, irrigation practices, and crop management strategies according to changing environmental conditions. In addition, digital platforms encourage peer-to-peer learning among farmers. Through online groups and forums, farmers can exchange experiences, discuss challenges, and learn about successful farming practices adopted by others.

5. Benefits of Digital Extension Services

Digital extension services offer numerous advantages that contribute to agricultural development.

- Wider Reach
- Timely Information Delivery
- Cost Efficiency
- Improved Decision-Making
- Enhanced Farmer Participation

ISSN: 3049-2289

Table 2. Comparison of Traditional and Digital Extension Approaches

Aspect	**Traditional Extension**	**Digital Extension**
Communication	Face-to-face meetings	Online and mobile-based
Reach	Limited to local farmers	Large-scale outreach
Information Speed	Slow	Instant
Cost	Higher operational costs	Lower communication cost
Interaction	Mostly one-way	Interactive communication

6. Challenges in Implementing Digital Extension Services

Despite the many advantages of digital extension services, several challenges remain. Limited digital infrastructure in rural areas can restrict access to internet-based platforms. In some regions, unreliable electricity supply and weak mobile networks hinder the effective use of digital technologies. Another important challenge is digital literacy among farmers. Many farmers may not be familiar with using smartphones, mobile applications, or online platforms. Training programs are necessary to improve farmers' ability to use digital tools effectively. Language barriers also limit the accessibility of digital extension services. Agricultural information must be available in local languages to ensure that farmers from different regions can easily understand it. Ensuring the accuracy and reliability of digital information is another important concern. Farmers must receive trustworthy and scientifically validated information to make correct decisions.

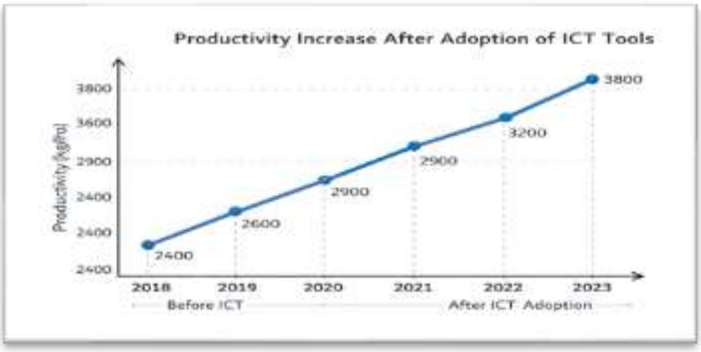


Figure 2. Impact of Digital Extension on Agricultural Productivity

7. Strategies to Strengthen Digital Extension Systems

`Strengthening digital extension systems requires coordinated efforts from governments, research institutions, private technology companies, and farmer organizations. Investment in rural digital infrastructure, including broadband connectivity and mobile networks, is essential for expanding digital extension services. Training programs should be conducted to improve farmers' digital literacy and awareness of ICT tools. User-friendly applications designed in local languages can further increase adoption among farmers. Collaboration between public institutions and private technology providers can help develop innovative digital platforms that support agricultural development.

8. Future Prospects of Digital Agriculture

Emerging technologies such as Artificial Intelligence (AI), Internet of Things (IoT), big data analytics, and blockchain are expected to further transform agricultural extension systems. AI-powered advisory platforms can analyse large datasets and generate customized recommendations for farmers. IoT devices such as soil sensors and automated irrigation systems can monitor field conditions in real time and improve resource management. Big data analytics can help predict pest outbreaks, climate trends, and crop yields. The integration of these technologies will create a smart agriculture ecosystem where farmers receive precise and data-driven recommendations.

9. Conclusion

Digital extension services are transforming agricultural knowledge dissemination by integrating ICT tools with traditional extension approaches. These technologies enable farmers to access timely and reliable information that supports better decision-making and improved farm productivity. Although challenges such as limited digital infrastructure and low digital literacy remain, continued investment in technology, training, and policy support can help overcome these barriers. As agriculture continues to evolve in the digital age, ICT-driven extension services will play a critical role in empowering farmers, enhancing agricultural productivity, and ensuring sustainable food systems.

References

1. Bhat, P. P., R., R., A., K., Jadhav, A., M. K. N., R. C. M., & Reddy, S. L. (2024). The role of Information and Communication Technology (ICT) in enhancing the effectiveness of agricultural extension programs worldwide: A review. *Journal of Scientific Research and Reports*.
2. Byamukama, W., Ssemakula, E., Ssekandi, J., Shaman, A., Businge, P., Kalibwani, R., Atukunda, C., & Turyasingura, B. (2025). A review of ICT integration in agricultural extension services: A global perspective. *East African Journal of Interdisciplinary Studies*.
3. Dujali, I. L., Inutan, S. M. B., Bacus, M. S., Quijano-Pagutayao, A., & Sarita, V. B. (2025). Transforming agricultural extension in the digital age: A review of ICT-based approaches and innovations. *International Journal of Research and Scientific Innovation*.
4. Giulivi, N., Harou, A. P., Gautam, S., & Guereña, D. (2022). Getting the message out: Information and communication technologies and agricultural extension. *American Journal of Agricultural Economics*, 104(5), 1914–1940.
5. Khan, R. P., Gupta, S., Daum, T., Birner, R., & Ringler, C. (2024). Levelling the field: A review of the ICT revolution and agricultural extension in the Global South. *Journal of International Development*.
6. Khatri, A., Lallawmkimi, M. C., Rana, P., Panigrahi, C. K., Minj, A., Koushal, S., & Ali, M. U. (2024). Integration of ICT in agricultural extension services: A review. *Journal of Experimental Agriculture International*.
7. Mapiye, C., Makombe, G., Molotsi, A., Dzama, K., & Mapiye, O. (2021). Towards a revolutionized agricultural extension system for the sustainability of smallholder livestock production in developing countries: The potential role of ICTs. *Sustainability*, 13(11), 6084.
8. Mapiye, O., Makombe, G., Molotsi, A., Dzama, K., & Mapiye, C. (2021). Information and communication technologies (ICTs): The potential for enhancing the dissemination of agricultural information and services to smallholder farmers in sub-Saharan Africa. *Information Development*, 37(4), 564–578.
9. Mukherjee, S., Padaria, R., Burman, R. R., Velayudhan, P. K., Mahra, G., Aditya, K., … Gopalakrishna Bhat, A. (2025). Global trends in ICT-based extension and advisory services in agriculture: A bibliometric analysis. *Frontiers in Sustainable Food Systems*.
10. Nyarko, D. A., & Kozári, J. (2021). Information and communication technologies (ICTs) usage among agricultural extension officers and its impact on extension delivery in Ghana. *Journal of the Saudi Society of Agricultural Sciences*, 20(6), 389–399.

AGRICULTURE BULLETIN
ISSN: 3049-2289

E-Extension Platforms and Their Impact on Farmer Awareness and Technology Adoption

Nikhil Thakur and Sumesh Sharma
Research Scholar, Department of Social Science, College of Forestry, Dr. Yashwant Singh Parmar University of Horticulture and Forestry
Research Scholar, Department of Agricultural Extension and Communication, College of Agriculture, Swami Keshwanand Rajasthan Agricultural University, Bikaner – 334006, Rajasthan, India

Agricultural development depends greatly on the effective transfer of knowledge from research institutions to farmers. Traditionally, extension systems relied on field demonstrations, training programmes, and personal visits by extension officers to communicate improved farming practices. Although these approaches have contributed significantly to agricultural growth, they often face challenges such as limited manpower, geographical constraints, and delays in delivering timely information. The emergence of digital technologies has opened new opportunities for strengthening agricultural extension services. Among these innovations, electronic extension or e-extension platforms have gained considerable importance in recent years. E-extension refers to the use of digital tools such as mobile applications, online advisory portals, interactive websites, and multimedia communication systems to deliver agricultural information to farmers. These platforms provide easy access to information on crop management, pest and disease control, weather forecasts, market prices, and government schemes. By enabling rapid dissemination of information, e-extension platforms play a crucial role in improving farmer awareness and encouraging the adoption of modern agricultural technologies. Farmers can obtain expert advice without the need for frequent visits to extension offices, thereby saving time and resources. In addition, the interactive nature of many e-extension systems allows farmers to ask questions, share field observations, and receive recommendations tailored to their specific conditions. Despite these advantages, challenges such as digital literacy, infrastructure limitations, and information reliability remain important concerns. Addressing these issues is essential for ensuring that e-extension platforms effectively support agricultural development. This article discusses the concept of e-extension, explores major platforms used in agricultural communication, examines their impact on farmer awareness and technology adoption, and highlights strategies to strengthen digital extension systems for sustainable agricultural growth.

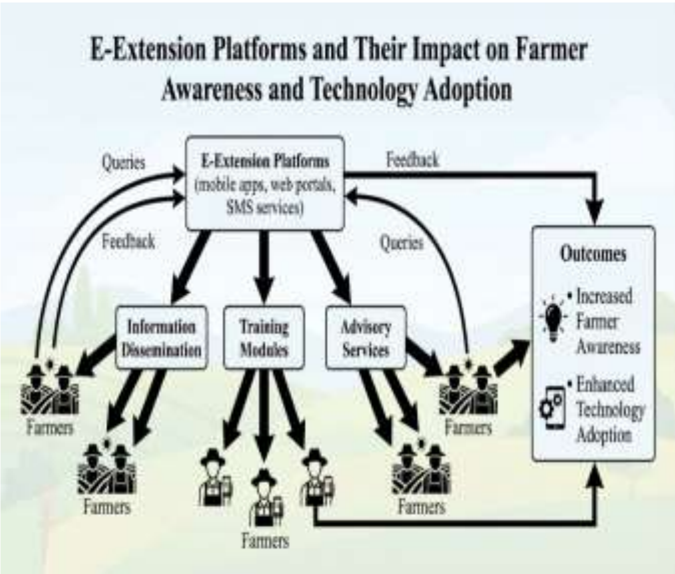
Introduction

Agriculture has always been closely linked with the availability and use of knowledge. Farmers need timely and accurate information to make decisions regarding crop selection, nutrient management, pest control, irrigation scheduling, and marketing strategies. Agricultural extension systems were established to ensure that scientific knowledge generated in research institutions reaches farmers and contributes to improved productivity and sustainability. Traditionally, extension activities relied on personal communication methods such as farm visits, demonstrations, group meetings, training sessions, and printed advisory materials. These methods have proven effective in many contexts, yet they often struggle to reach large numbers of farmers due to limited human resources and logistical constraints.

The rapid development of information and communication technologies has begun to transform the way agricultural information is shared. With increasing access to smartphones, mobile networks,

ISSN: 3049-2289

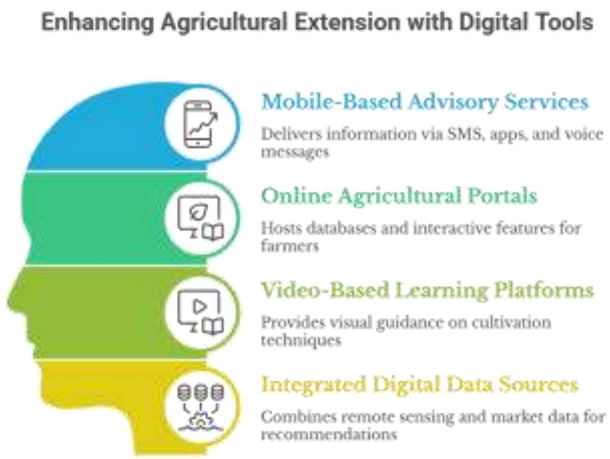
and the internet, farmers are gradually becoming part of the digital information ecosystem. In this changing environment, e-extension platforms have emerged as innovative tools that complement conventional extension approaches. These platforms enable the dissemination of agricultural knowledge through digital channels such as websites, mobile applications, SMS services, video tutorials, and interactive advisory systems. E-extension platforms are particularly valuable because they allow information to be delivered quickly and efficiently to a wide audience. Instead of waiting for scheduled training sessions or extension visits, farmers can access information whenever they need it. Digital advisory systems also enable scientists and extension personnel to respond to farmers' queries more rapidly, reducing delays in problem diagnosis and management. As a result, e-extension platforms are increasingly recognized as important components of modern agricultural knowledge systems.



Concept and Components of E-Extension

E-extension refers to the application of digital technologies to support agricultural extension services. It involves the use of electronic communication tools to disseminate information, provide advisory services, and facilitate knowledge exchange among farmers, scientists, and extension professionals. The primary objective of e-extension is to improve the accessibility, speed, and effectiveness of agricultural communication. Several types of platforms are commonly used in e-extension systems. Mobile-based advisory services deliver information directly to farmers through SMS alerts, mobile applications, or voice messages. These services often provide updates on weather forecasts, pest outbreaks, fertilizer recommendations, and market prices. Because mobile phones are widely available even in rural areas, mobile-based platforms are among the most widely adopted forms of digital extension. Online agricultural portals and websites represent another important component of e-extension. These platforms host large databases of information related to crop production, soil health, integrated pest management, and farm mechanization. Farmers and extension workers can access these resources to learn about recommended practices and emerging technologies. Many portals also include interactive features that allow users to submit questions and receive expert responses.

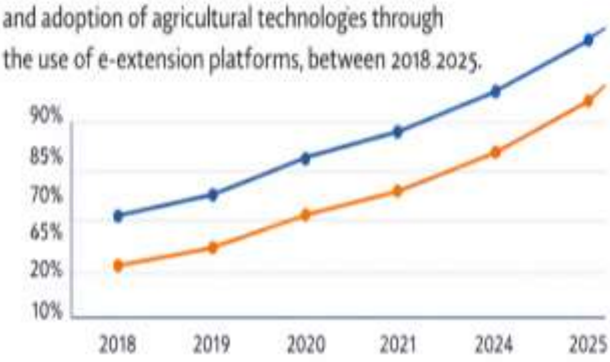
Video-based learning platforms have also become increasingly popular in agricultural communication. Short instructional videos demonstrating cultivation techniques, pest management strategies, or machinery operation provide farmers with clear visual guidance that is often easier to understand than written instructions. Such multimedia content helps bridge the gap between scientific knowledge and practical implementation in the field. Another important aspect of e-extension is the integration of digital data sources such as remote sensing, weather forecasting systems, and market information networks. By combining these data sources with advisory services, e-extension platforms can deliver location-specific recommendations that support better decision making by farmers.



Impact of E-Extension on Farmer Awareness

One of the most significant contributions of e-extension platforms is the improvement of farmer awareness. Access to timely information enables farmers to stay informed about new technologies, improved crop varieties, and modern management practices. Digital platforms allow farmers to learn about innovations that may not yet be widely adopted in their local communities. This exposure to new ideas helps create a more informed and progressive farming environment. E-extension platforms also facilitate continuous learning among farmers. Traditional extension programmes often provide information during specific training sessions, which may occur only once or twice a year. In contrast, digital platforms allow farmers to access information whenever they need it. This flexibility encourages farmers to explore different topics and update their knowledge regularly. Another important benefit is the ability of e-extension systems to provide real-time updates. Weather changes, pest outbreaks, and market fluctuations can significantly affect agricultural decisions. Through digital alerts and notifications, farmers can receive immediate information that helps them respond quickly to emerging challenges. For example, early warnings about pest infestations enable farmers to implement control measures before the problem spreads widely. The interactive nature of many e-extension platforms further enhances farmer awareness. Farmers can submit questions, share field observations, and discuss farming experiences with experts and fellow farmers. Such interactions promote collaborative learning and help farmers gain confidence in adopting new practices.

Figure 2. Increasing trend in farmer awareness and adoption of agricultural technologies through the use of e-extension platforms, between 2018 2025.



Influence on Technology Adoption

Increased awareness often leads to greater willingness to adopt improved agricultural technologies. When farmers understand the benefits and practical requirements of a technology, they are more likely to integrate it into their farming systems. E-extension platforms contribute to this process by providing clear explanations, demonstrations, and success stories related to new agricultural innovations. Digital advisory systems allow farmers to observe the experiences of other farmers who have successfully implemented a technology. Seeing practical results through videos, testimonials, or case studies reduces uncertainty and encourages adoption. Farmers can also compare different management approaches and evaluate which practices are most suitable for their specific conditions. Another important factor influencing technology adoption is the availability of timely technical support. Farmers may hesitate to adopt new practices if they are unsure how to implement them correctly. E-extension platforms address this concern by providing continuous access to expert advice. Farmers can seek clarification whenever they encounter difficulties,

ISSN: 3049-2289

which reduces the perceived risk associated with adopting new technologies.

E-extension also supports the dissemination of information about government schemes, subsidies, and training opportunities related to agricultural technologies. By making this information easily accessible, digital platforms encourage farmers to participate in development programmes and adopt improved practices that enhance productivity and sustainability.

Challenges in Implementing E-Extension Systems

Despite the promising potential of e-extension platforms, several challenges limit their widespread adoption. One of the most significant barriers is the uneven distribution of digital infrastructure in rural areas. Reliable internet connectivity and electricity are essential for accessing online platforms, yet these resources are not always available in remote farming communities. Digital literacy is another important issue. Some farmers may lack the skills required to operate smartphones, navigate websites, or interpret digital information. Without proper training, these farmers may not be able to benefit fully from e-extension services. Capacity-building programmes that teach farmers how to use digital tools are therefore essential for maximizing the impact of e-extension systems. The credibility and reliability of online information also present challenges. Because digital platforms allow many individuals to share content, inaccurate or misleading information may sometimes circulate among users. Ensuring that advisory messages originate from credible institutions and qualified experts is crucial for maintaining trust in e-extension systems. Language barriers may also reduce the effectiveness of digital communication. Many agricultural resources are published in English or other widely used languages that may not be familiar to all farmers. Providing information in local languages and using simple, clear communication styles can greatly improve the accessibility of digital extension services.

Strategies for Strengthening E-Extension Platforms

To enhance the effectiveness of e-extension systems, coordinated efforts are required from research institutions, extension agencies, government organizations, and private technology providers. One important strategy is the development of user-friendly digital platforms that are easy for farmers to navigate. Interfaces should be designed with simple menus, visual icons, and clear instructions to ensure accessibility even for users with limited technical experience. Improving digital infrastructure in rural areas is another key priority. Investments in internet connectivity, mobile networks, and reliable power supply can significantly expand the reach of e-extension services. Government initiatives that promote rural digital development play a vital role in supporting this process. Training programmes that build digital skills among farmers and extension workers are equally important. Farmers who understand how to use smartphones, search for reliable information, and communicate through digital platforms are more likely to benefit from e-extension services. Extension personnel also need training to effectively manage online advisory systems and respond to farmers' queries in a timely manner. Collaboration between research institutions and digital technology providers can further improve the quality of e-extension platforms. Integrating scientific databases, weather information systems, and market intelligence networks into digital advisory platforms allows farmers to receive more comprehensive and location-specific recommendations.

Conclusion

E-extension platforms represent a significant advancement in agricultural communication systems. By leveraging digital technologies, these platforms enable faster and more efficient dissemination of agricultural knowledge, thereby improving farmer awareness and supporting the adoption of modern technologies. Farmers benefit from timely access to expert advice, multimedia learning resources, and interactive communication channels that connect them directly with researchers and extension professionals. At the same time, scientists gain valuable insights into field-level challenges through feedback provided by farmers. Although challenges related to digital literacy, infrastructure, and information reliability still exist, strategic investments in training, technology development, and institutional collaboration can greatly enhance the effectiveness of e-extension systems. As agriculture continues to evolve in the digital age, e-extension platforms are likely to play an increasingly important role in promoting sustainable farming practices and strengthening the link between research and practical application in the field.

References:

1. Awad, M. (2021). Digitization of agricultural extension. International Journal of Modern Agriculture and Environment, 1(2), 99–112.
2. Fabregas, R., Kremer, M., & Schilbach, F. (2019). Realizing the potential of digital development: The case of agricultural advice. Science, 366(6471), eaay3038. https://doi.org/10.1126/science.aay3038
3. Khatri, A., Lallawmkimi, M. C., Rana, P., Panigrahi, C. K., Minj, A., Koushal, S., & Ali, M. U. (2024). Integration of ICT in agricultural extension services: A review. Journal of Experimental Agriculture International, 46(12), 1–17. https://doi.org/10.9734/jeai/2024/v46i122590
4. Mukherjee, S., Padaria, R., Burman, R. R., Velayudhan, P. K., Mahra, G., Aditya, K., … Bhat, A. G. (2025). Global trends in ICT-based extension and advisory services in agriculture: A bibliometric analysis. Frontiers in Sustainable Food Systems, 9, 1450873. https://doi.org/10.3389/fsufs.2025.1450873
5. Priya, N. K., Patil, S. S., Vishwakarma, S. K., Saikanth, D. R. K., Mishra, I., Tripathi, S., Shastri, S. (2025). Digital innovations in extension education: A review of emerging technologies and their impact on agricultural knowledge dissemination. Journal of Experimental Agriculture International, 47(3), 1–18. https://doi.org/10.9734/jeai/2025/v47i32456
6. Impact on awareness and technology adoption
7. Beach, R. H., Milliken, C., Franzen, K., & Lapidus, D. (2025). Meta-analysis of the impacts of digital information interventions on agricultural development. Global Food Security, 38, 100722. https://doi.org/10.1016/j.gfs.2025.100722
8. Giulivi, N., Harou, A. P., Gautam, S., & Guereña, D. (2022). Getting the message out: Information and communication technologies and agricultural extension. American Journal of Agricultural Economics, 104(6), 2384–2410. https://doi.org/10.1111/ajae.12345
9. Li, B., Zhuo, N., Ji, C., & Zhu, Q. (2022). Influence of smartphone-based digital extension service on farmers' sustainable agricultural technology adoption in China. International Journal of Environmental Research and Public Health, 19(15), 9390.
10. Singh, N. K., Sunitha, N., Tripathi, G., Saikanth, D. R. K., Sharma, A., Jose, A. E., & Mary, M. (2023). Impact of digital technologies in agricultural extension. Asian Journal of Agricultural Extension, Economics & Sociology, 41(9), 963–970.

AGRICULTURE BULLETIN
ISSN: 3049-2289

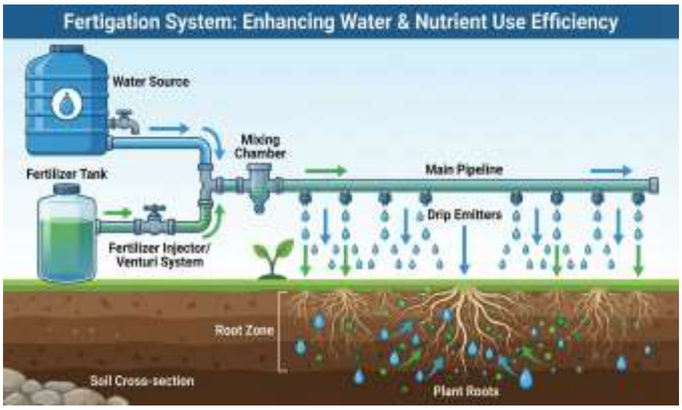
Fertigation Techniques for Enhancing Fertilizer Use Efficiency and Crop Yield

Yashika Mandela
Ph.D., Division of Soil Science and Water Management, Dr. Yashwant Singh Parmar University of Horticulture and Forestry, Nauni (Solan), Himachal Pradesh, India

Fertigation, the application of fertilizers through irrigation systems, is a pivotal agronomic practice aimed at improving fertilizer use efficiency (FUE) and crop yield. This review synthesizes current knowledge on fertigation techniques, their operational principles, benefits, challenges, and impacts on nutrient management and crop productivity. Emphasis is placed on different fertigation systems, nutrient delivery optimization, environmental implications, and future prospects for sustainable agriculture. The review also explores recent technological advancements, practical considerations for widespread adoption, and integration with emerging agricultural practices.

1.Introduction

Efficient fertilizer management remains a cornerstone of sustainable crop production, resource conservation, and environmental stewardship. Traditional fertilizer application methods such as broadcasting, banding, and manual side-dressing often lead to substantial nutrient losses through leaching, volatilization, and surface runoff. These inefficiencies not only reduce nutrient uptake by plants but also contribute to environmental degradation, including groundwater contamination and greenhouse gas emissions. Fertigation, the practice of applying water-soluble fertilizers through irrigation systems, offers a promising alternative by enabling precise, timely, and site-specific nutrient delivery directly to the root zone. This integration of fertilization and irrigation enhances nutrient availability, minimizes losses, and improves crop productivity. This review provides a comprehensive examination of fertigation techniques, underlying mechanisms, agronomic benefits, operational challenges, environmental impacts, and future directions to optimize fertilizer use efficiency and crop yield.



2. Principles of Fertigation

Fertigation involves the dissolution of water-soluble fertilizers into irrigation water, which is then delivered through various irrigation systems such as drip, sprinkler, or center pivot systems. The core principles guiding fertigation practices are:

a) **Synchronization of Nutrient Supply with Crop Demand:** Nutrient application schedules are designed to coincide with specific phenological stages of crop growth, ensuring that essential nutrients are available during periods of peak demand. This dynamic nutrient management contrasts with conventional static application methods, reducing nutrient wastage and improving uptake efficiency.

b) **Spatial Precision:** Fertilizers are applied directly to the rhizosphere, minimizing heterogeneity in nutrient distribution and reducing losses to non-target zones such as surface runoff or deep percolation.

c) **Water and Nutrient Conservation:** By integrating irrigation and fertilization, fertigation optimizes the use of both water and nutrients, reducing input wastage and mitigating environmental contamination risks.

d) **Flexibility and Control:** Fertigation systems permit real-time adjustments in nutrient types, concentrations, and application timing based on crop needs, soil conditions, and environmental factors. This adaptability supports precision agriculture objectives.

e) **Reduction of Nutrient Toxicity Risks:** Controlled nutrient delivery prevents the buildup of toxic concentrations in the root zone, promoting healthier root development and overall plant vigor.

3. Types of Fertigation Systems

a) **Drip Fertigation:** Drip irrigation combined with fertigation is recognized as the most efficient nutrient delivery system. Emitters placed near the root zone deliver water and nutrients in precise quantities, minimizing leaching and volatilization. This system is particularly advantageous for high-value horticultural crops, greenhouse production, and regions facing water scarcity. The localized application reduces weed growth and soil erosion, further enhancing sustainability.

b) **Sprinkler Fertigation:** Fertilizers dissolved in irrigation water are sprayed over the crop canopy or soil surface. While less precise than drip systems, sprinkler fertigation is widely used in row crops, orchards, and large-scale farms due to its ability to cover extensive areas efficiently. However, nutrient losses via evaporation, wind drift, and uneven distribution pose challenges that can reduce fertilizer use efficiency.

c) **Surface and Subsurface Irrigation Fertigation:** Fertilizers are applied through flood, furrow, or basin irrigation in surface systems or injected into subsurface irrigation lines. These methods are generally less efficient due to uneven nutrient distribution, higher risks of runoff, and leaching. Nevertheless, they remain prevalent in regions lacking advanced irrigation infrastructure. Innovations such as gated pipe systems and surge irrigation aim to improve nutrient uniformity in these contexts.

d) **Center Pivot and Lateral Move Systems:** In large-scale cereal and forage production, center pivot and lateral move irrigation systems can be adapted for fertigation. These mechanized systems enable automated nutrient application but require careful management to address issues of nutrient stratification and uniformity.

Table 1: Comparison of Different Fertigation Systems

Fertigation System	Efficiency Level	Precision of Nutrient Delivery	Suitable Crops/Area	Key Advantages	Limitations
Drip Fertigation	Very High (85–95%)	Very High	Vegetables, fruits, greenhouse	Precise application, minimal losses	High initial cost
Sprinkler	Moderate	Moderate	Field crops,	Covers large area, easy	Evaporation & wind drift

Fertigation	(70–85%)		orchards	operation	losses
Surface/Subsurface Fertigation	Low–Moderate (50–70%)	Low	Traditional farming systems	Low cost, simple system	Uneven distribution, leaching losses
Center Pivot/Lateral Move	Moderate–High (75–90%)	Moderate–High	Large-scale cereals & forage	Automation, large area coverage	Requires careful management & investment

4. Benefits of Fertigation for Fertilizer Use Efficiency

a) **Enhanced Nutrient Uptake:** Fertigation maintains a steady supply of nutrients in the root zone, keeping soil nutrient concentrations within optimal ranges for absorption. This continuous availability supports sustained physiological functions, root elongation, and nutrient transport mechanisms.

b) **Reduced Fertilizer Losses:** Precise nutrient delivery minimizes leaching into groundwater, surface runoff, and gaseous losses such as ammonia volatilization and nitrous oxide emissions. These reductions are critical for mitigating environmental pollution and aligning with regulatory frameworks.

c) **Improved Crop Growth and Yield:** Optimized nutrient availability facilitates enhanced photosynthetic capacity, enzyme activities, and reproductive development, leading to increased biomass production, better fruit set, and higher grain yields.

d) **Resource Use Efficiency:** Integrating water and nutrient management reduces the total inputs required per unit of crop output, lowering production costs and conserving scarce resources such as water and synthetic fertilizers.

e) **Flexibility in Nutrient Management:** Fertigation supports the simultaneous application of macro- and micronutrients, including trace elements and growth regulators, enabling tailored nutrient regimes that address specific crop deficiencies and physiological needs.

f) **Reduction in Labor and Energy Costs:** Automated fertigation systems decrease labor requirements associated with manual fertilizer application and reduce energy consumption by optimizing irrigation schedules.

5. Impact of Fertigation on Crop Yield

Numerous studies across diverse agro-ecological zones and cropping systems have demonstrated that fertigation can increase crop yields by 10-30% compared to conventional fertilization practices. The yield improvements are attributed to enhanced nutrient availability during critical growth stages such as vegetative growth, flowering, fruit set, and grain filling.

a) **Vegetables:** In crops such as tomato, cucumber, and pepper, fertigation has resulted in increased fruit size, improved quality attributes (e.g., sugar content, firmness, and shelf life), and higher total yields. The precise nutrient supply reduces physiological disorders like blossom end rot and enhances uniformity in fruit development.

ISSN: 3049-2289

b) **Fruit Crops:** Citrus, grapes, apples, and other fruit crops benefit from fertigation through improved fruit size, sugar accumulation, acidity balance, and yield consistency. Fertigation also supports better nutrient balance, reducing incidences of nutrient-related disorders and enhancing post-harvest quality.

c) **Cereals:** In staple cereals like maize, wheat, and rice, fertigation enhances grain yield, protein content, and nutrient density. Timely nutrient supply during critical phenological stages such as tillering, booting, and grain filling improves yield components like kernel number and weight.

d) **Specialty Crops:** High-value crops such as flowers, medicinal plants, and spices respond well to fertigation with increased biomass, improved secondary metabolite production, and enhanced quality traits.

e) **Case Studies:** Field trials in semi-arid regions have demonstrated that drip fertigation in tomato cultivation can increase yield by up to 25%, while reducing water consumption by 30-40%. Similarly, fertigation in vineyards has led to yield increases of 15-20% with improved berry quality parameters.

6. Nutrient Management Strategies in Fertigation

Effective fertigation requires comprehensive nutrient management planning to optimize fertilizer use efficiency and crop performance:

a) **Nutrient Formulation:** Selection of water-soluble fertilizers that meet crop-specific nutrient requirements is essential. Balanced formulations containing macronutrients (nitrogen, phosphorus, potassium) and essential micronutrients (zinc, iron, manganese, copper, boron) are critical for preventing deficiencies and toxicities.

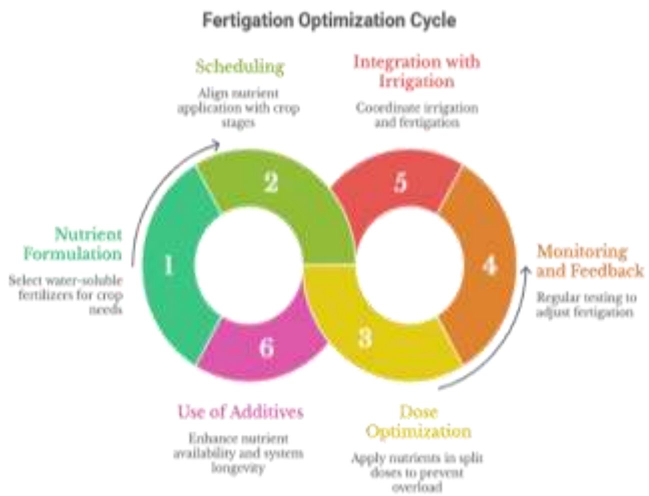
b) **Scheduling:** Fertilizer application timing is synchronized with crop phenological stages to align nutrient availability with physiological demand peaks. This involves dividing total nutrient requirements into multiple split applications to maintain steady nutrient supply.

c) **Dose Optimization:** Applying nutrients in split doses prevents nutrient overload, reduces toxicity risks, and minimizes environmental losses. Dose adjustments are informed by soil nutrient status, crop growth rate, and environmental conditions.

d) **Monitoring and Feedback:** Regular soil testing, plant tissue analysis, and nutrient solution monitoring provide feedback for adjusting fertigation regimes. These diagnostics ensure nutrient supply remains within optimal ranges and prevent deficiencies or excesses.

e) **Integration with Irrigation Management:** Coordinated irrigation and fertigation scheduling ensure adequate water availability for nutrient uptake while avoiding water stress or waterlogging. Soil moisture sensors and evapotranspiration data can guide irrigation timing and volumes.

f) **Use of Additives:** Incorporation of chelating agents, pH stabilizers, and anti-clogging additives in fertigation solutions can enhance nutrient availability and system longevity.



7. Challenges and Limitations

Despite its numerous benefits, fertigation faces several operational and adoption challenges:

a) **System Clogging:** Precipitation of insoluble compounds and accumulation of suspended particles can block emitters, reducing system efficiency. This necessitates effective filtration, regular maintenance, and use of compatible fertilizer formulations with minimal precipitate potential.

b) **Initial Investment and Operational Costs:** The capital expenditure for fertigation infrastructure, including pumps, filters, injectors, and control units, can be prohibitive, particularly for smallholder farmers. Operational costs related to energy, maintenance, and skilled labor also impact adoption.

c) **Technical Expertise Requirements:** Successful fertigation demands knowledge of crop nutrient dynamics, irrigation scheduling, water quality management, and system maintenance. Lack of technical capacity can lead to suboptimal application, nutrient imbalances, and system failures.

d) **Risk of Over-Fertilization and Environmental Impact:** Poorly managed fertigation can result in nutrient overload, causing phytotoxicity, soil salinization, and environmental pollution through runoff and leaching.

e) **Water Quality Constraints:** High salinity, alkalinity, or presence of certain ions in irrigation water can interact with fertilizers, causing precipitation and clogging issues.

f) **Infrastructure Limitations:** In regions with unreliable water supply, inadequate irrigation infrastructure, or lack of electricity, fertigation implementation is constrained.

g) **Crop and Soil Specificity:** Fertigation suitability varies with crop type, root architecture, and soil properties. Some crops or soils may not respond optimally due to nutrient fixation, uneven distribution, or root zone constraints.

8. Environmental Implications

Fertigation supports environmentally sustainable agriculture by:

a) **Reducing Nutrient Losses:** Precise nutrient delivery minimizes leaching and runoff, reducing eutrophication risks in aquatic ecosystems and protecting groundwater quality.

b) **Conserving Water Resources:** Efficient irrigation scheduling and localized nutrient application reduce overall water use, critical in water-scarce regions.

c) **Lowering Carbon Footprint:** Optimized fertilizer use reduces the energy-intensive manufacture and application of fertilizers, lowering greenhouse gas emissions associated with agriculture.

d) **Mitigating Soil Degradation:** Balanced nutrient application prevents soil acidification, salinization, and nutrient imbalances, preserving soil health and productivity.

e) **Supporting Integrated Nutrient Management:** Fertigation complements organic amendments, crop rotations, and conservation agriculture, enhancing nutrient cycling and system resilience.

f) **Reducing Pesticide Use:** Improved nutrient status can enhance plant health and resistance, potentially reducing the need for chemical pest control.

9. Advances and Future Prospects

Emerging technologies and practices are poised to enhance fertigation efficiency and adoption:

a) **Automation and Sensor Integration:** Real-time soil moisture and nutrient sensors coupled with automated control systems enable dynamic fertigation scheduling, optimizing nutrient delivery in response to crop and environmental conditions.

b) **Controlled-Release and Slow-Release Fertilizers:** Integration of these fertilizers with fertigation systems can modulate nutrient release rates, improving synchronization with crop demand and reducing losses.

c) **Decision Support Systems (DSS):** AI-driven DSS utilize environmental, crop, and soil data to generate optimized fertigation schedules, nutrient formulations, and doses, enhancing precision and reducing user error.

d) **Remote Monitoring and IoT:** Internet of Things (IoT) technologies facilitate remote system monitoring, diagnostics, and management, reducing labor and improving responsiveness.

e) **Nanotechnology:** Development of nano-fertilizers compatible with fertigation may improve nutrient use efficiency through enhanced solubility, targeted delivery, and controlled release.

f) **Policy and Extension Support:** Government subsidies, training programs, and extension services play crucial roles in promoting fertigation adoption, particularly among smallholders and resource-poor farmers.

g) **Integration with Sustainable Practices:** Combining fertigation with conservation agriculture, organic amendments, crop diversification, and agroforestry can enhance system resilience, biodiversity, and long-term productivity.

h) **Climate Change Adaptation:** Fertigation offers adaptive potential by improving water and nutrient use efficiency under variable climatic conditions, supporting crop resilience against drought and heat stress.

10. Conclusion

Fertigation constitutes a transformative approach to nutrient management, significantly enhancing fertilizer use efficiency and crop yield while promoting environmental sustainability. By enabling precise, timely, and site-specific nutrient delivery, fertigation supports the sustainable intensification of agriculture, conserving vital resources and mitigating negative environmental impacts. Addressing the technical, economic, and knowledge barriers through technological innovation, policy frameworks, and farmer capacity building is essential to unlocking the full potential of fertigation globally. Ongoing research and development efforts should focus on optimizing fertigation practices across diverse agro-ecological zones, cropping systems, and socio-economic contexts to ensure equitable and sustainable agricultural productivity.

References

Ashrafi, M. R., Raj, M., Shamim, S., Lal, K., & Kumar, G. (2020). Effect of fertigation on crop productivity and nutrient use efficiency. *Journal of Pharmacognosy and Phytochemistry*, *9*(5), 2937-2942.

Jat, R. A., Wani, S. P., Sahrawat, K. L., Singh, P., & Dhaka, P. L. (2011). Fertigation in vegetable crops for higher productivity and resource use efficiency. *Indian Journal of fertilizers*, *7*(3), 22-37.

Al-Wabel, M. I., Al-Jaloud, A. A., Hussain, G., & Karimula, S. (2004, June). Fertigation as a tool to improve nitrogen use efficiency and yield. In *International Symposium on Greenhouses, Environmental Controls and In-house Mechanization for Crop Production in the Tropics 710* (pp. 295-300).

Sarma, H. H., Paul, A., Kakoti, M., & Talukdar, N. (2023). Fertigation: a modern approach for enhancing nutrient use efficiency in. *Frontiers in Agricultural Sustainability*.

AGRICULTURE BULLETIN
ISSN: 3049-2289

Engineered Biochar for Enhanced Soil Water Retention in Arid and Semi-Arid Regions

Shilpa Bhandary
M.Sc. (Agriculture), Department of Soil Science, Sam Higginbottom University of Agriculture, Technology and Sciences, Prayagraj, Uttar Pradesh, India

Arid and semi-arid regions face severe limitations in agricultural productivity due to scarce water resources and poor soil water retention capacities. Engineered biochar, a carbon-rich material derived from biomass pyrolysis and further modified through physical, chemical, or biological processes, has emerged as a promising soil amendment to enhance soil water retention, improve soil health, and boost crop productivity in these challenging environments. This comprehensive review discusses the properties of engineered biochar relevant to soil water retention, the mechanisms by which it modifies soil physical and chemical characteristics, production techniques, practical applications in dryland agriculture, challenges, and future research directions aimed at sustainable land management under water scarcity.

1.Introduction

Agriculture in arid and semi-arid regions is constrained primarily by limited and erratic rainfall, high evapotranspiration rates, and soils with low water holding capacity. These factors result in frequent drought stress, reduced crop yields, and land degradation. Traditional soil amendments such as organic matter additions or clay incorporation have shown limited success in significantly improving soil water retention in these environments. Biochar, produced by pyrolyzing biomass under limited oxygen conditions, has attracted attention due to its porous structure, high surface area, and chemical stability, which collectively improve soil physical, chemical, and biological properties. Engineered biochar refers to biochar that has been intentionally modified or optimized to enhance specific functionalities, including water retention, nutrient holding capacity, and microbial interactions. This article delves into the role of engineered biochar as a sustainable amendment to increase soil water retention in arid and semi-arid regions, thereby enhancing agricultural resilience and productivity.

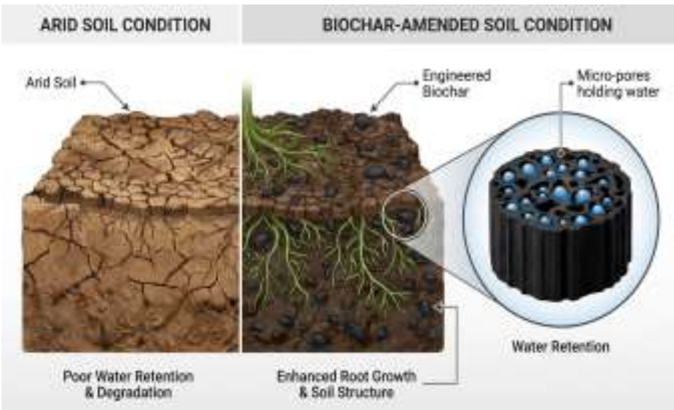


Figure 1: Engineered biochar for soil water retention

2. Properties of Engineered Biochar Relevant to Soil Water Retention

a) **Porosity and Surface Area:** Engineered biochars are designed to possess a high volume of micro-, meso-, and macropores that increase the soil's capacity to adsorb and retain water. The enhanced surface area facilitates greater water adsorption onto biochar surfaces and within its pores, acting as a reservoir for soil moisture.

b) **Hydrophilicity:** Chemical modifications such as oxidation, acid or base treatments, or impregnation with hydrophilic substances increase the affinity of biochar surfaces for water molecules. These modifications introduce functional groups (e.g., carboxyl, hydroxyl) that

ISSN: 3049-2289

enhance moisture retention through hydrogen bonding and electrostatic attraction.

c) **Particle Size and Structure:** Tailoring particle size distribution and surface morphology influences pore connectivity and water movement within the soil matrix. Smaller particles increase surface area but may reduce macroporosity, while larger particles improve aeration and water infiltration.

d) **Cation Exchange Capacity (CEC):** Enhanced CEC through chemical treatments improves nutrient retention, which indirectly supports soil structure and water retention by maintaining aggregate stability and reducing nutrient leaching.

e) **Stability and Longevity:** Engineered biochars are designed for long-term persistence in soil, resisting microbial degradation and physical breakdown, thereby providing sustained improvements in soil water retention over multiple growing seasons.

Table 1: Types of Engineered Biochar and Their Characteristics

Type of Engineered Biochar	Modification Method	Key Properties Enhanced
Activated Biochar	Thermal/physical activation	High surface area, porosity
Acid-treated Biochar	Chemical treatment (HCl)	Improved hydrophilicity
Mineral-enriched Biochar	Impregnation (Ca, Mg, Fe)	Nutrient retention, structure
Polymer-coated Biochar	Polymer coating	Water retention & slow release
Biochar with microbes	Microbial inoculation	Biological activity

3. Mechanisms of Soil Water Retention Enhancement by Engineered Biochar

a) **Physical Water Holding:** The porous architecture of biochar traps water within micro- and mesopores, increasing the soil's field capacity and available water content. This trapped water is slowly released to plant roots, mitigating drought stress.

b) **Improved Soil Aggregation:** Biochar promotes the formation and stabilization of soil aggregates by binding soil particles together, which enhances soil porosity, improves water infiltration, and reduces surface crusting and evaporation losses.

c) **Hydrophilic Surface Interactions:** Engineered biochar surfaces with hydrophilic functional groups attract and retain water molecules more effectively than unmodified biochar, increasing the soil moisture retention capacity.

d) **Water Release Dynamics:** The slow desorption of water from biochar pores provides a controlled release of moisture during dry periods, supporting continuous plant water availability.

e) **Enhanced Microbial Activity:** Biochar serves as a habitat and energy source for beneficial soil microbes, which contribute to organic matter decomposition and soil structure formation, indirectly enhancing soil water retention.

4. Engineered Biochar Production Techniques

a) **Physical Modification:** Techniques such as steam activation, ball milling, and ultrasonic treatment increase biochar porosity and surface area. Steam activation opens additional pores and cleans surfaces, while ball milling reduces particle size and alters surface morphology.

b) **Chemical Modification:** Treatment with acids (e.g., nitric, phosphoric), bases (e.g., potassium hydroxide), or oxidizing agents introduces oxygen-containing functional groups to biochar surfaces, enhancing hydrophilicity and CEC. These treatments also help remove ash and impurities, improving biochar quality.

c) **Composite Biochars:** Combining biochar with hydrogels, clays, polymers, or other amendments creates composites with superior water absorption and retention properties. Hydrogels, for example, can absorb many times their weight in water and release it slowly.

d) **Biological Treatments:** Inoculation of biochar with beneficial microbes or enzymes modifies surface chemistry and promotes soil microbial colonization, enhancing soil biological activity and water retention.

5. Application of Engineered Biochar in Arid and Semi-Arid Soils

a) **Improving Soil Moisture Retention:** Engineered biochar amendments increase soil field capacity and available water content, especially in sandy and degraded soils that characterize many arid and semi-arid regions. This enhancement reduces the frequency and severity of drought stress.

b) **Enhancing Crop Water Use Efficiency:** By maintaining higher soil moisture levels, biochar reduces plant water stress, supports physiological processes such as photosynthesis and nutrient uptake, and improves water use efficiency.

c) **Mitigating Soil Erosion and Degradation:** Biochar's role in stabilizing soil aggregates reduces erosion risks by improving soil structure and increasing organic matter content. This is particularly important in fragile dryland ecosystems prone to degradation.

d) **Supporting Drought Resilience:** Engineered biochar acts as a buffer during intermittent droughts by sustaining moisture availability, thereby improving crop survival and yield stability under water-limited conditions.

e) **Integration with Other Practices:** Combining biochar with mulching, conservation tillage, efficient irrigation methods (e.g., drip irrigation), and organic amendments maximizes soil water retention and overall soil health.

6. Case Studies and Field Trials

a) **Vegetable Production in Semi-Arid Regions:** Field trials applying oxidized biochar with hydrophilic functional groups at rates of 5-10 t/ha demonstrated a 15-25% increase in soil moisture retention. This translated into approximately 20% higher yields under deficit irrigation regimes, highlighting biochar's role in mitigating water stress.

b) **Rangeland Restoration:** In degraded arid rangelands, steam-activated biochar applications (8-12 t/ha) improved soil aggregation and moisture retention, resulting in enhanced vegetation cover and ecosystem resilience. These improvements contribute to carbon sequestration and land rehabilitation efforts.

c) **Cereal Crop Improvement:** Studies in sandy soils amended with composite biochar-hydrogel blends (3-8 t/ha) showed a 10-30% increase in grain yield for wheat and maize under limited rainfall conditions. Enhanced water use efficiency and nutrient retention were key drivers of these gains.

7. Challenges and Considerations

a) **Feedstock Variability:** The properties and performance of biochar depend heavily on the biomass source and pyrolysis conditions, leading to variability in water retention capacity and nutrient interactions. Standardization remains a challenge.

b) **Cost and Scalability:** Production and modification of engineered biochar can be resource-intensive, requiring specialized equipment and energy inputs. This limits large-scale adoption, especially in resource-poor regions.

c) **Soil-Biochar Interactions:** Long-term effects of biochar on soil chemistry and biology are not fully understood. Potential risks include nutrient imbalances, changes in soil pH, and unintended impacts on soil microbial communities.

d) **Application Rates and Methods:** Optimal biochar dosage and incorporation techniques vary with soil type, crop species, and environmental conditions. Over-application may lead to negative effects such as water repellency or nutrient immobilization.

e) **Environmental Impacts:** Biochar production involves greenhouse gas emissions and energy use. Ensuring sustainable sourcing of feedstock and clean production methods is essential to minimize environmental footprints.

f) **Water Quality Constraints:** Irrigation water with high salinity or specific ion content can interact adversely with biochar, affecting its structure and function.

8. Environmental Implications

a) **Reduced Nutrient Leaching:** By improving nutrient retention alongside water retention, engineered biochar reduces nutrient losses to groundwater, mitigating eutrophication risks.

b) **Water Conservation:** Enhanced soil moisture retention reduces irrigation water requirements, supporting water conservation in water-scarce regions.

c) **Carbon Sequestration:** Biochar's stable carbon structure contributes to long-term soil carbon storage, mitigating climate change impacts.

d) **Soil Health Improvement:** Balanced nutrient supply and improved soil structure foster resilient soil ecosystems, supporting sustainable agricultural productivity.

e) **Reduced Soil Degradation:** Biochar applications help prevent soil acidification, salinization, and erosion, preserving soil fertility.

9. Advances and Future Prospects

a) **Nano-Engineered Biochars:** Development of nano-scale biochars with enhanced surface properties may further improve water retention and nutrient delivery efficiency.

b) **Smart Biochars:** Integration of biochar with responsive materials or sensors could allow dynamic regulation of soil moisture and nutrient availability.

c) **Synergistic Amendments:** Combining biochar with organic matter, biofertilizers, or moisture-retaining polymers could create multifunctional soil amendments tailored to specific agro-ecological zones.

d) **Automation and Monitoring:** Use of remote sensing, IoT, and AI-driven decision support systems can optimize biochar application timing, rates, and management in precision agriculture frameworks.

ISSN: 3049-2289

e) **Policy and Extension Support:** Incentives, subsidies, and farmer education programs are critical to promote biochar adoption, especially among smallholder farmers in arid and semi-arid regions.

f) **Climate Change Adaptation:** Engineered biochar offers adaptive capacity by improving water and nutrient use efficiency under increasingly variable and extreme climatic conditions.

g) **Long-Term Field Studies:** Expanded multi-season and multi-location trials are needed to validate sustained benefits, optimize practices, and assess environmental impacts.

10. Conclusion

Engineered biochar represents a promising and innovative approach to enhancing soil water retention in arid and semi-arid regions, addressing critical constraints to agricultural productivity and ecosystem sustainability. By improving soil physical structure, water holding capacity, and nutrient retention, biochar supports crop resilience against drought and contributes to sustainable land management. Overcoming challenges related to production costs, standardization, and long-term soil interactions through technological innovation, policy support, and farmer engagement will be essential to harnessing the full potential of engineered biochar. Continued interdisciplinary research and field validation will enable tailored biochar solutions that enhance agricultural productivity and environmental health in water-limited environments.

References

Xiao, Q., Zhu, L. X., Shen, Y. F., & Li, S. Q. (2016). Sensitivity of soil water retention and availability to biochar addition in rainfed semi-arid farmland during a three-year field experiment. *Field Crops Research*, *196*, 284-293.

Mohamed, B. A., Ellis, N., Kim, C. S., Bi, X., & Emam, A. E. R. (2016). Engineered biochar from microwave-assisted catalytic pyrolysis of switchgrass for increasing water-holding capacity and fertility of sandy soil. *Science of the Total Environment*, *566*, 387-397.

Alotaibi, K. D., & Schoenau, J. J. (2019). Addition of biochar to a sandy desert soil: effect on crop growth, water retention and selected properties. *Agronomy*, *9*(6), 327.

Baiamonte, G., Minacapilli, M., & Crescimanno, G. (2020). Effects of biochar on irrigation management and water use efficiency for three different crops in a desert sandy soil. *Sustainability*, *12*(18), 7678.

Ndede, E. O., Kurebito, S., Idowu, O., Tokunari, T., & Jindo, K. (2022). The potential of biochar to enhance the water retention properties of sandy agricultural soils. *Agronomy*, *12*(2), 311.

Abrol, V., Ben-Hur, M., Verheijen, F. G., Keizer, J. J., Martins, M. A., Tenaw, H., ... & Graber, E. R. (2016). Biochar effects on soil water infiltration and erosion under seal formation conditions: rainfall simulation experiment. *Journal of Soils and Sediments*, *16*(12), 2709-2719.

AGRICULTURE BULLETIN
ISSN: 3049-2289

Integrating Biochar with Biofertilizers for Sustainable Soil Management

Vaibhav Shivaji Chakor, Atharva Laxman More, and Rishikesh Shivprasad Patil
M.Sc. (Agriculture) Soil Science, Research Executive, Center of Excellence (CoE), Urban Farms Co., India
M.Sc. (Agriculture) Soil Science, R&D Operation Associate, Division of Biochar Fertilizer and R&D, MASH MAKES, India
B.Sc. (Hons.) Agriculture, Senior Soil Analyst, Division of Biochar Fertilizer and R&D, MASH MAKES, India

The integration of biochar with biofertilizers presents a promising approach to sustainable soil management by enhancing soil fertility, improving nutrient use efficiency, and mitigating environmental impacts associated with conventional agriculture. Biochar, a stable carbon-rich material derived from biomass pyrolysis, improves soil physical and chemical properties, while biofertilizers introduce beneficial microorganisms that promote nutrient cycling and plant growth. This comprehensive review examines the synergistic effects of combining biochar and biofertilizers, exploring their mechanisms, impacts on soil health, crop productivity, and environmental sustainability. Challenges, knowledge gaps, and future research directions for optimizing this integrated approach are also discussed, highlighting its potential role in advancing climate-smart and regenerative agriculture.

1.Introduction

Sustainable soil management is fundamental to global food security, environmental protection, and climate change mitigation. Conventional agricultural practices heavily reliant on synthetic fertilizers and intensive tillage have led to soil degradation, loss of biodiversity, and increased greenhouse gas emissions. These challenges necessitate the adoption of integrated soil fertility management strategies that incorporate organic amendments and beneficial microorganisms to restore soil health and promote sustainable crop production.

Biochar and biofertilizers represent two complementary components of such strategies. Biochar is a carbonaceous material produced through pyrolysis of organic biomass under oxygen-limited conditions. Its unique physicochemical properties, including high porosity, surface area, and chemical stability, improve soil structure, water retention, and nutrient holding capacity. Biofertilizers, comprising living beneficial microorganisms such as nitrogen-fixing bacteria, phosphate-solubilizing bacteria, and mycorrhizal fungi, enhance nutrient availability, uptake, and plant growth.

The integration of biochar with biofertilizers leverages the physical and chemical advantages of biochar as a habitat and carrier for microorganisms, potentially enhancing microbial survival, activity, and efficacy. This synergistic approach can improve soil fertility, increase crop yields, and reduce dependency on synthetic fertilizers, contributing to climate-smart and regenerative agricultural systems.

This review provides a detailed examination of biochar and biofertilizers, their individual and combined effects on soil health and crop productivity, underlying mechanisms, empirical evidence, challenges, and future perspectives for sustainable soil management.

ISSN: 3049-2289

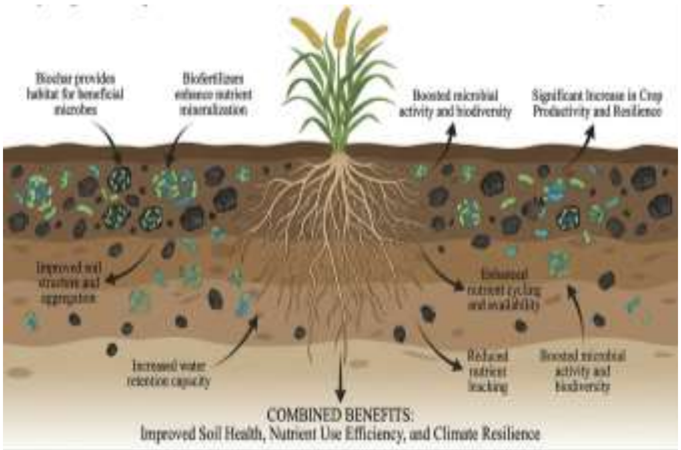


Figure 1: Integrating Biochar with Biofertilizers for Sustainable Soil Management

2. Biochar: Properties and Role in Soil Management

2.1 Production and Physicochemical Characteristics

Biochar is produced by pyrolyzing biomass feedstocks such as agricultural residues, forestry waste, and animal manures at temperatures typically ranging from 300°C to 700°C under oxygen-limited conditions. The pyrolysis process results in a carbon-rich, porous material with a stable aromatic carbon structure resistant to microbial degradation. The properties of biochar, including surface area, porosity, pH, cation exchange capacity (CEC), and nutrient content, are influenced by feedstock type and pyrolysis conditions.

2.2 Soil Physical Improvements

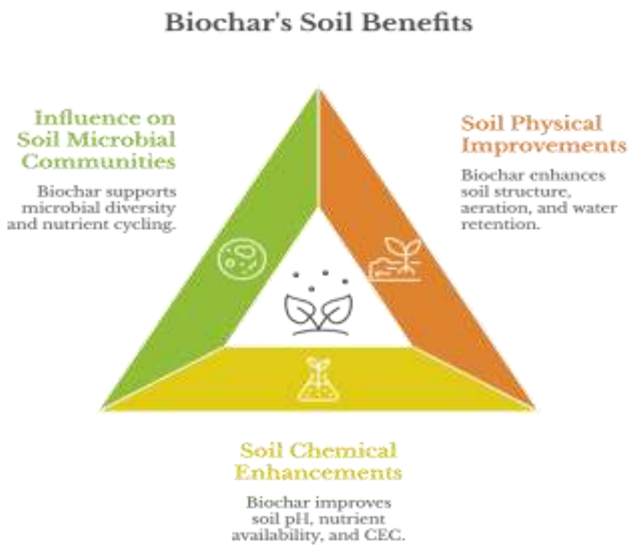
Biochar enhances soil physical properties by increasing porosity and aggregation, which improves aeration, water infiltration, and root penetration. Its porous matrix acts as a reservoir for water, enhancing soil moisture retention, particularly in sandy or degraded soils prone to drought. Improved soil structure reduces bulk density and compaction, facilitating better root growth and microbial habitat.

2.3 Soil Chemical Enhancements

The alkaline nature of most biochars raises soil pH, ameliorating acidic soils and improving nutrient availability. Biochar's high surface area and functional groups (carboxyl, hydroxyl, phenolic) increase soil CEC, promoting nutrient retention and reducing leaching losses of essential cations such as potassium, calcium, and magnesium. Biochar can adsorb ammonium and phosphate ions, enhancing nutrient availability over time.

2.4 Influence on Soil Microbial Communities

Biochar provides a protective habitat for soil microorganisms within its pores, shielding them from desiccation, predation, and environmental fluctuations. This habitat supports microbial colonization and biofilm formation, increasing microbial biomass and diversity. Biochar amendments have been shown to stimulate microbial enzymatic activities involved in nutrient cycling, such as nitrogen fixation, nitrification, and phosphorus solubilization.



3. Biofertilizers: Types, Functions, and Mechanisms

3.1 Classification and Microbial Types

Biofertilizers consist of living microorganisms that promote plant growth by enhancing nutrient availability and uptake. Major types include:

ISSN: 3049-2289

a) **Nitrogen-fixing bacteria:** Rhizobium (symbiotic), Azotobacter, Azospirillum (free-living).

b) **Phosphate-solubilizing bacteria (PSB):** Species of Pseudomonas, Bacillus, and Enterobacter that convert insoluble phosphates into bioavailable forms.

c) **Potassium-solubilizing bacteria (KSB):** Mobilize potassium from mineral sources.

d) **Mycorrhizal fungi:** Arbuscular mycorrhizal fungi (AMF) form symbiotic associations with roots, extending hyphal networks for enhanced nutrient and water uptake.

e) **Plant Growth-Promoting Rhizobacteria (PGPR):** Produce phytohormones, siderophores, and enzymes that stimulate growth and stress tolerance.

3.2 Mechanisms of Action

Biofertilizers improve plant nutrition and growth through multiple mechanisms:

a) **Nutrient Mobilization:** Fix atmospheric nitrogen, solubilize phosphates and potassium, and mineralize organic matter.

b) **Phytohormone Production:** Synthesize auxins, gibberellins, cytokinins, enhancing root growth and development.

c) **Disease Suppression:** Induce systemic resistance and produce antimicrobial compounds reducing pathogen incidence.

d) **Stress Alleviation:** Enhance plant tolerance to abiotic stresses by modulating antioxidant systems and osmoprotectant synthesis.

4. Synergistic Integration of Biochar and Biofertilizers

4.1 Biochar as a Microbial Carrier

Biochar's porous structure and high surface area provide an ideal microhabitat for biofertilizer microorganisms. It protects microbes from environmental stresses such as UV radiation, desiccation, and predation, improving their survival during storage and after soil application. Biochar surfaces facilitate microbial adhesion and biofilm formation, stabilizing microbial populations and enhancing their interaction with plant roots.

4.2 Enhanced Microbial Activity and Nutrient Cycling

The combined application of biochar and biofertilizers stimulates microbial biomass and enzymatic activities critical for nutrient cycling. Biochar amendments increase soil microbial diversity and abundance, promoting processes such as nitrogen fixation, nitrification, and phosphate solubilization. This synergism enhances nutrient availability and turnover, supporting plant growth.

4.3 Improved Nutrient Use Efficiency and Crop Productivity

Integration of biochar and biofertilizers enhances nutrient retention in soils, reducing losses through leaching and volatilization. This leads to increased nutrient uptake by plants, improved biomass accumulation, and higher yields. The combined use is particularly effective in nutrient-poor or degraded soils where nutrient use efficiency is low.

4.4 Environmental Benefits

By reducing reliance on synthetic fertilizers, the biochar-biofertilizer combination lowers greenhouse gas emissions, particularly nitrous oxide (N_2O), and reduces nutrient runoff, mitigating eutrophication risks. Biochar's carbon sequestration potential further contributes to climate change mitigation.

Table 1: Functional Roles of Biochar and Biofertilizers in Sustainable Soil Management

Parameter	Biochar Role	Biofertilizer Role	Integrated Effect (Synergy)
Soil Organic Carbon (SOC)	Provides stable carbon (recalcitrant)	Enhances carbon mineralization	Improves both stable and active carbon pools
Soil Structure	Enhances porosity and aggregation	Produces binding agents (EPS)	Improved aggregation and soil tilth
Microbial Activity	Provides habitat for microbes	Introduces beneficial microorganisms	Increased microbial biomass and diversity
Nutrient Availability	Adsorbs and retains nutrients	Fixes and solubilizes nutrients	Enhanced nutrient cycling and availability
Nitrogen Dynamics	Reduces N losses (leaching/volatilization)	Biological N fixation	Improved nitrogen use efficiency (NUE)
Phosphorus Availability	Adsorbs P and reduces fixation	Solubilizes insoluble phosphates	Increased P availability to plants
Water Holding Capacity	High due to porous structure	Improves root growth and uptake	Enhanced soil moisture retention
Soil pH Regulation	Alkaline nature buffers acidic soils	Microbial processes stabilize pH	Balanced soil pH conditions
Greenhouse Gas Emissions	Reduces N_2O and CH_4 emissions	Improves nutrient efficiency	Overall mitigation of GHG emissions
Soil Health Index	Improves physical properties	Enhances biological properties	Holistic improvement in soil health

5. Empirical Evidence and Case Studies

5.1 Soil Fertility and Microbial Dynamics

Numerous studies report that biochar combined with nitrogen-fixing bacteria increases soil nitrogen content, microbial biomass carbon, and enzymatic activities such as dehydrogenase and phosphatase. Phosphate-solubilizing bacteria inoculated with biochar improve soil available phosphorus and microbial diversity, enhancing nutrient cycling.

5.2 Crop Growth and Yield Enhancement

Field and pot experiments demonstrate that integrating biochar with biofertilizers such as Rhizobium, Azospirillum, or AMF significantly improves plant height, leaf area, chlorophyll content, root development, and grain yield in cereals, legumes, and horticultural crops. The synergistic effects often surpass those of individual applications.

5.3 **Stress Mitigation**

Combined application enhances plant tolerance to abiotic stresses like drought and salinity by improving soil moisture retention, nutrient availability, and inducing systemic resistance via microbial metabolites. Biochar's water retention properties coupled with microbial production of osmoprotectants and antioxidants support plant resilience.

6. Mechanistic Insights

6.1 Microbial Colonization and Biofilm Formation

Biochar surfaces facilitate microbial adhesion and biofilm development, creating stable microbial communities that enhance nutrient solubilization and plant-microbe interactions. Biofilms increase microbial resistance to environmental stresses and improve colonization efficiency of the rhizosphere.

6.2 Nutrient Adsorption and Release

Biochar adsorbs nutrients and microbial exudates, creating nutrient-rich microhabitats that sustain microbial metabolism. This adsorption modulates nutrient release kinetics, enhancing nutrient availability synchronously with plant demand.

6.3 Soil-Plant-Microbe Interactions

The integrated system alters soil physicochemical properties and microbial community structure, influencing root exudation patterns and signaling pathways that regulate nutrient uptake, hormone signaling, and plant growth.

7. Challenges and Limitations

7.1 Variability in Biochar and Biofertilizer Quality

Differences in feedstock types, pyrolysis conditions, and microbial strains result in variability in biochar properties and biofertilizer efficacy. This inconsistency complicates standardization and reproducibility of results.

7.2 Optimal Application Rates and Methods

Lack of consensus on appropriate dosages and application techniques for combined use affects effectiveness and scalability. Over-application may lead to nutrient imbalances or microbial inhibition.

7.3 Soil and Environmental Influences

Soil texture, pH, climate, and cropping systems influence the performance of biochar-biofertilizer integration, necessitating site-specific evaluations and tailored management.

7.4 Microbial Viability and Compatibility

Maintaining microbial viability during biochar incorporation and ensuring compatibility with indigenous soil microbiota are technical challenges requiring optimized formulations and delivery systems.

8. Future Perspectives and Research Directions

8.1 Standardization and Quality Control

Development of standardized protocols for biochar production and biofertilizer formulation is essential to ensure consistent quality, efficacy, and regulatory acceptance.

8.2 Mechanistic and Molecular Studies

Advanced molecular, imaging, and omics techniques should be employed to elucidate microbial colonization dynamics, gene expression, and interactions within the biochar-microbe-plant system.

8.3 Formulation Innovation

Designing biochar-based biofertilizer carriers with tailored physical and chemical properties can enhance microbial survival, targeted nutrient release, and field performance.

ISSN: 3049-2289

8.4 **Field Validation and Scaling**

Long-term, multi-location field trials are necessary to assess agronomic benefits, environmental impacts, and economic viability across diverse agroecosystems.

8.5 **Integration with Sustainable Practices**

Combining biochar-biofertilizer technology with organic amendments, conservation agriculture, and precision farming can optimize soil health management.

8.6 **Policy, Extension, and Farmer Engagement**

Developing supportive policies, extension services, and participatory research approaches will facilitate adoption and scaling among farmers.

9. Conclusion

The integration of biochar with biofertilizers offers a synergistic and sustainable strategy for enhancing soil fertility, nutrient use efficiency, and crop productivity while mitigating environmental impacts. Biochar's unique physicochemical properties create a conducive habitat and carrier for beneficial microorganisms, amplifying biofertilizer efficacy. Despite challenges related to variability, application, and environmental factors, ongoing research and technological advances provide promising avenues for optimizing this integration. Adoption of biochar-biofertilizer systems can significantly contribute to climate-smart agriculture, soil regeneration, and sustainable food production, aligning with global goals for environmental sustainability and resilience.

References

Ajeng, A. A., Abdullah, R., & Ling, T. C. (2023). Biochar-Bacillus consortium for a sustainable agriculture: physicochemical and soil stability analyses. *Biochar*, *5*(1), 17.

Bong, C. P. C., Lim, L. Y., Lee, C. T., Ong, P. Y., Van Fan, Y., & Klemeš, J. J. (2021). Integrating compost and biochar towards sustainable soil management. *Chemical Engineering Transactions*, *86*, 1345-1350.

Shikha, F. S., Rahman, M. M., Sultana, N., Mottalib, M. A., & Yasmin, M. (2023). Effects of biochar and biofertilizer on groundnut production: a perspective for environmental sustainability in Bangladesh. *Carbon Research*, *2*(1), 10.

Bohn, S. M. (2025). Sustainable Soil Management: The Impact of Biochar and Microbial Inoculants on Crop Yield and Soil Health. *Europian Journal of Crop Science and Technology P-ISSN 3051-0139 E-ISSN 3051-0147*, *1*(01), 9-16.

Khan, M. A., Basir, A., Shah, S. T., Rehman, M. U., Hassan, M. U., Zheng, H., ... & Mancinelli, R. (2024). Sustainable soil management in alkaline soils: The role of biochar and organic nitrogen in enhancing soil fertility. *Land*, *13*(11), 1869.

AGRICULTURE BULLETIN
ISSN: 3049-2289

Synergistic Effects of Biochar and Compost on Soil Carbon Sequestration and Crop Climate Resilience

Reenu Verma
Ph.D. Scholar, Division of Environmental Sciences, ICAR- Indian Agricultural Research Institute, New Delhi, India

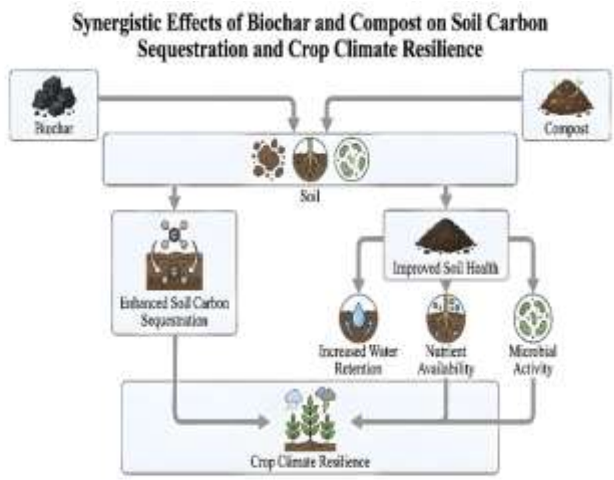
The combined application of biochar and compost in agricultural soils is gaining recognition as an effective approach to enhance soil carbon sequestration and improve crop resilience under climate change. This article provides a comprehensive examination of the mechanisms, benefits, and challenges associated with the synergistic use of these organic amendments. It details how biochar's stable carbon matrix and compost's nutrient-rich organic matter interact to improve soil physical, chemical, and biological properties, leading to increased soil organic carbon (SOC) stocks and enhanced crop tolerance to abiotic stresses. The discussion integrates current scientific insights, addresses environmental and agronomic implications, and highlights future research directions for optimizing this promising climate-smart agricultural practice.

1.Introduction

Climate change poses significant threats to global agriculture by intensifying abiotic stresses such as drought, heat, and soil degradation. These stressors jeopardize food security and necessitate sustainable soil management strategies that both mitigate greenhouse gas emissions and bolster crop productivity. Soil carbon sequestration, the process of capturing atmospheric carbon dioxide (CO_2) in soil organic matter (SOM), emerges as a critical strategy to address these challenges.

Biochar and compost represent two organic amendments with distinct but complementary properties. Biochar is produced through pyrolysis of biomass, resulting in a carbon-rich, porous material with high chemical stability. Compost is the product of aerobic decomposition of organic wastes, rich in nutrients and labile organic compounds that stimulate microbial activity. While individually beneficial, their combined application has shown potential for synergistic effects, enhancing carbon stabilization and crop resilience more effectively than either amendment alone.

This article explores these synergistic effects in detail, focusing on soil carbon dynamics, microbial interactions, and crop climate resilience, providing a robust framework for integrating biochar and compost into sustainable agricultural systems.



2. Soil Carbon Sequestration: Concepts and Significance

Soil carbon sequestration involves the accumulation and long-term storage of carbon in soil organic matter, reducing atmospheric CO_2 levels. The process depends on carbon inputs (plant residues, organic amendments), decomposition rates, and stabilization mechanisms such as physical protection within aggregates and chemical recalcitrance.

Enhancing SOC improves soil structure, water retention, nutrient availability, and microbial habitats, which are essential for maintaining crop productivity and resilience. However, SOC is vulnerable to loss through mineralization, especially under intensive cultivation and climate stress, making the adoption of carbon-stabilizing amendments critical.

3. Biochar: Characteristics and Role in Carbon Sequestration

Biochar is distinguished by its porous structure, high surface area, and aromatic carbon content, which confer resistance to microbial breakdown. Its application contributes to:

1. **Long-Term Carbon Storage:** The recalcitrant nature of biochar carbon ensures persistence in soils over decades to centuries, making it a stable carbon sink.
2. **Soil Physical Enhancement:** Biochar improves soil porosity and water-holding capacity, mitigating drought stress and improving aeration.
3. **Chemical Interactions:** It adsorbs nutrients and organic molecules, reducing leaching and enhancing nutrient retention in the root zone.
4. **Microbial Habitat Provision:** The porous matrix serves as a refuge for beneficial microbes, facilitating enhanced biochemical soil processes.

Biochar's efficacy depends on feedstock type, pyrolysis temperature, and soil characteristics, necessitating tailored applications.

4. Compost: Properties and Contributions to Soil Health

Compost is rich in labile organic matter and essential nutrients such as nitrogen (N), phosphorus (P), and potassium (K). Its application leads to:

1. **Nutrient Cycling Enhancement:** Compost mineralizes nutrients, making them bioavailable for plant uptake.
2. **Microbial Stimulation:** It increases microbial biomass and diversity, accelerating organic matter decomposition and nutrient turnover.
3. **Soil Structure Improvement:** Compost enhances aggregate stability and porosity.
4. **Carbon Input:** Although compost carbon is more labile than biochar, it contributes to SOC through microbial biomass formation and humification.

The quality and maturity of compost influence its agronomic effectiveness.

5. Synergistic Effects of Biochar and Compost on Soil Carbon Dynamics

The co-application of biochar and compost induces synergistic effects that enhance soil carbon sequestration through multiple interconnected mechanisms:

1. **Enhanced Carbon Stabilization:** Biochar's aromatic, recalcitrant carbon adsorbs labile organic compounds from compost, reducing their decomposition rate and promoting humic substance formation. This process transforms labile carbon into more stable SOC fractions.
2. **Improved Microbial Efficiency and Community Structure:** Compost provides readily available substrates and nutrients, stimulating microbial activity. Biochar's porous structure offers protective microhabitats, fostering a diverse, metabolically active microbial community that efficiently converts organic inputs into stable SOC.
3. **Aggregate Formation and Physical Protection:** Biochar particles serve as nucleation sites for soil aggregates, while compost-derived organic matter acts as a binding agent. Enhanced aggregation physically shields organic carbon from microbial attack, increasing SOC persistence.

ISSN: 3049-2289

4. **Reduction of Greenhouse Gas Emissions:** The biochar-compost mixture mitigates emissions of CO_2, methane (CH_4), and nitrous oxide (N_2O) during organic matter decomposition. Biochar's adsorption of ammonium reduces nitrification and denitrification, limiting N_2O emissions, while improved soil aeration curtails CH_4 production.

5. **Increased Total SOC Stocks:** Field and laboratory studies consistently show higher SOC accumulation in soils receiving combined biochar and compost amendments compared to individual treatments. The degree of increase is influenced by soil type, climate, and management practices.

Table 1: Synergistic Effects of Biochar and Compost on Soil Carbon Sequestration and Crop Climate Resilience

Parameter	Biochar Alone	Compost Alone	Biochar + Compost (Synergistic Effect)
Soil Organic Carbon (SOC)	Stable carbon, long-term sequestration	Labile carbon, rapid decomposition	Enhanced SOC stability + increased carbon input
Carbon Sequestration Potential	High (recalcitrant carbon)	Moderate (short-term storage)	Very high due to combined stable + active carbon pools
Soil Structure	Improves porosity and aggregation	Enhances soil aggregation	Strong aggregation and improved soil tilth
Microbial Activity	Moderate (limited nutrients)	High (rich in nutrients)	Very high due to habitat (biochar) + nutrients (compost)
Nutrient Availability	Adsorbs nutrients, reduces leaching	Supplies readily available nutrients	Improved nutrient retention and slow-release availability
Water Holding Capacity	High due to porous structure	Moderate	Significantly enhanced moisture retention
Soil pH Regulation	Increases pH (alkaline nature)	Slight buffering effect	Balanced pH stabilization
Greenhouse Gas Emissions	Reduces N_2O and CH_4 emissions	May increase emissions initially	Net reduction in GHG emissions over time
Crop Yield Stability	Moderate improvement	High short-term improvement	High and stable yields under stress conditions
Climate Resilience	Enhances drought	Improves nutrient	Strong resilience to drought,

	tolerance	resilience	heat, and nutrient stress
Longevity of Effects	Long-term	Short to medium-term	Both immediate and sustained benefits

6. Impact on Crop Climate Resilience

Crop resilience to climate-induced abiotic stresses is enhanced by biochar and compost through various pathways:

1. **Improved Water Retention and Drought Mitigation:** Biochar's porosity and compost's organic matter increase soil moisture availability, buffering crops against water deficits.
2. **Enhanced Nutrient Supply and Uptake Efficiency:** Compost supplies essential nutrients, while biochar retains these nutrients in the root zone, improving nutrient use efficiency under stress.
3. **Promotion of Beneficial Soil Microbial Communities:** The amendments support populations of mycorrhizal fungi and plant growth-promoting rhizobacteria, which enhance nutrient acquisition and stress tolerance.
4. **Soil pH Buffering:** Biochar can neutralize acidic soils, improving nutrient availability and root growth under challenging conditions.

Empirical evidence from field trials indicates improved crop yields, physiological health (e.g., chlorophyll content, stomatal conductance), and stress tolerance when biochar and compost are applied together.

7. Mechanistic Insights into Synergistic Interactions

Understanding the underlying mechanisms is essential for optimizing biochar-compost co-application:

1. **Chemical Interactions:** Biochar adsorbs dissolved organic carbon and nutrients released from compost, reducing losses via leaching and volatilization and stabilizing labile carbon compounds.
2. **Microbial Community Dynamics:** The amendments create a heterogeneous soil environment supporting diverse microbial taxa, including bacteria, fungi, and archaea. Biochar provides refugia protecting microbes from environmental stress, while compost supplies energy substrates, promoting beneficial microbial groups involved in nutrient cycling and plant stress resilience.
3. **Enhanced Soil Enzymatic Activities:** The biochar-compost mixture stimulates enzymes such as cellulases, phosphatases, and dehydrogenases, accelerating organic matter breakdown and nutrient mineralization, which promotes humic substance formation and sustained fertility.
4. **Soil Aggregate Stability:** Biochar acts as a scaffold for aggregate formation, while compost-derived polysaccharides and humic acids serve as binding agents. Stable aggregates protect SOC by limiting microbial access and improving soil aeration and moisture retention.

8. Factors Influencing Synergistic Effects

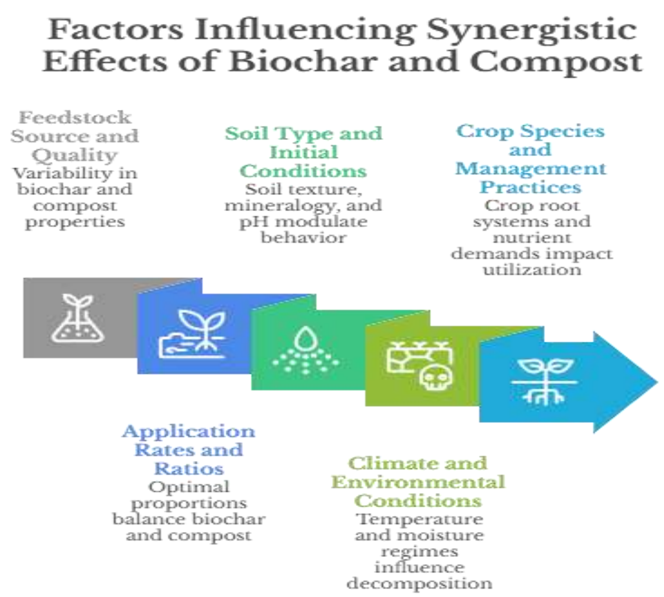
Several factors influence the effectiveness of biochar and compost co-application:

1. **Feedstock Source and Quality:** Variability in biochar and compost properties due to feedstock and production methods affects

ISSN: 3049-2289

nutrient content, carbon stability, and amendment interactions.

2. **Application Rates and Ratios:** Optimal proportions balance biochar's stable carbon with compost's nutrient-rich labile matter. Excessive biochar may immobilize nutrients, while excessive compost can accelerate carbon mineralization and greenhouse gas emissions.
3. **Soil Type and Initial Conditions:** Soil texture, mineralogy, organic matter content, and pH modulate amendment behavior. Sandy soils benefit more from water retention, whereas clay soils exhibit stronger chemical interactions.
4. **Climate and Environmental Conditions:** Temperature and moisture regimes influence decomposition rates and microbial activity, affecting amendment persistence and effectiveness.
5. **Crop Species and Management Practices:** Crop root systems, nutrient demands, and phenology impact amendment utilization. Integration with practices like cover cropping and reduced tillage further modulates outcomes.



9. Environmental and Agronomic Implications

1. **Climate Change Mitigation:** Enhanced SOC sequestration reduces atmospheric CO_2, contributing to greenhouse gas mitigation.
2. **Soil Fertility and Productivity:** Improved nutrient cycling and soil structure support sustainable crop yields.
3. **Waste Management:** Utilizing biomass residues for biochar and organic waste for compost promotes circular economy principles, reducing environmental pollution.
4. **Reduced Chemical Fertilizer Dependence:** Improved nutrient retention lowers fertilizer requirements, decreasing environmental contamination risks.

The integration of biochar and compost aligns with sustainable intensification and regenerative agriculture frameworks, promoting resilient and eco-friendly farming systems.

10. Challenges and Knowledge Gaps

1. **Long-Term Field Studies:** There is a lack of multi-year trials assessing the persistence and cumulative effects of combined amendments under diverse conditions.
2. **Standardization of Materials:** Variability in biochar and compost properties complicates recommendations and comparability across studies.
3. **Mechanistic Understanding:** Further research is needed on microbial interactions, enzymatic processes, and carbon stabilization pathways.
4. **Economic and Practical Feasibility:** Cost-benefit analyses and scalability assessments are required for widespread adoption.
5. **Interactions with Other Agricultural Practices:** The effects of biochar and compost in combination with fertilizers,

tillage, and crop rotations require further investigation.

11. Future Perspectives and Recommendations

1. Develop standardized production and characterization protocols for biochar and compost to ensure consistency.
2. Conduct integrated, multi-site field trials across varied agroecological zones to capture environmental variability.
3. Utilize advanced molecular and isotopic tools to elucidate microbial and carbon dynamics in amended soils.
4. Explore policy frameworks and incentives to encourage farmer adoption.
5. Investigate synergistic effects with other sustainable practices such as cover cropping and conservation tillage.

Optimizing biochar and compost co-application offers a promising pathway toward climate-smart agriculture and enhanced soil carbon management.

12. Conclusion

The synergistic application of biochar and compost offers a powerful strategy to enhance soil carbon sequestration and improve crop resilience under climate change. By combining biochar's recalcitrant carbon with compost's nutrient-rich, labile organic matter, this approach leverages complementary mechanisms that improve soil physical structure, chemical nutrient retention, and biological activity. While outcomes vary with site-specific factors, the integration of these amendments into sustainable agricultural systems holds promise for mitigating climate change impacts and supporting resilient food production. Continued research, standardization, and adaptive management are essential to fully realize the potential of biochar and compost synergy in global agroecosystems.

References

Ashraf, S. K., Ripta, S. K., Rana, M. T., & Islam, K. K. (2025). Biochar enhanced agroforestry systems for carbon sequestration, soil health and climate resilience. *Discover Forests*, *1*(1), 53.

Fischer, D., & Glaser, B. (2012). Synergisms between compost and biochar for sustainable soil amelioration. In *Management of organic waste*. IntechOpen.

Ramba, T., Rasyid, B., Kaimuddin, K., Utami, D. S., Lande, B. P. Y., & Stöber, S. (2026). Assessing compost-biochar synergy for boosting carbon sequestration and local katokkon chili agronomic performance for promoting low-emission, climate-adapted farming systems. *Journal of Ecological Engineering*, *27*(4), 151-162.

Shyam, S., Ahmed, S., Joshi, S. J., & Sarma, H. (2025). Biochar as a soil amendment: implications for soil health, carbon sequestration, and climate resilience. *Discover Soil*, *2*(1), 18.

Aubertin, M. L. (2022). *Biochar-compost mixtures: interactions and impact on carbon sequestration and soil fertility* (Doctoral dissertation, Sorbonne université).

Osman, A. M., Rekaby, S. A., Khalafalla, M. Y., & Awad, M. (2022). The combined effect of compost and biochar application on carbon sequestration and some soil properties. *Archives of Agriculture Sciences Journal*, *5*(3), 174-191.

AGRICULTURE BULLETIN
ISSN: 3049-2289

Use of Remote Sensing and GIS Tools in Precision Agronomy

Vishal Gupta and Ashutosh Kumar
Ph.D., Department of Soil and Water Conservation Engineering, ICAR-Indian Agricultural Research Institute, New Delhi, India
B.Sc. Hons. Agriculture, ICAR-Indian Agricultural Research Institute, New Delhi, India

Precision agronomy integrates advanced technologies to optimize crop production, resource use efficiency, and environmental sustainability. Remote sensing (RS) and Geographic Information Systems (GIS) are pivotal tools in this domain, enabling spatially explicit data acquisition, analysis, and decision-making. This comprehensive review explores the principles, applications, and benefits of RS and GIS in precision agronomy, focusing on crop monitoring, soil mapping, nutrient management, irrigation scheduling, pest and disease detection, and yield prediction. Challenges, recent technological advances, and future prospects for integrating RS and GIS into precision agriculture frameworks are also discussed.

1.Introduction

Precision agronomy aims to manage spatial and temporal variability within agricultural fields to enhance productivity, resource efficiency, and environmental stewardship. Conventional farming practices often apply uniform inputs across heterogeneous fields, leading to suboptimal resource use, increased production costs, and environmental degradation. The integration of remote sensing and geographic information systems offers a transformative approach to understanding and managing this variability by providing spatially explicit, timely, and actionable information. Remote sensing technologies capture data on crop and soil conditions through satellite, aerial, and proximal sensors, while GIS facilitates the storage, integration, visualization, and analysis of these data alongside other spatial datasets. Together, RS and GIS form the foundation of precision agronomy, enabling site-specific management practices that optimize input use and improve crop performance.

2. Fundamentals of Remote Sensing and GIS in Agriculture

2.1 Remote Sensing Principles

Remote sensing involves acquiring information about the Earth's surface without direct contact, using sensors that detect reflected or emitted electromagnetic radiation. Sensors operate across various spectral bands, including visible, near-infrared (NIR), shortwave infrared (SWIR), thermal infrared (TIR), and microwave regions. Multispectral sensors capture data in discrete bands, while hyperspectral sensors collect data in hundreds of narrow contiguous bands, allowing detailed spectral characterization of vegetation and soils. Thermal sensors measure surface temperature, providing insights into plant water stress and evapotranspiration. Microwave sensors, including radar, penetrate clouds and provide data on soil moisture and surface roughness. The choice of sensor and platform (satellite, UAV, aircraft, or ground-based) depends on spatial resolution, temporal frequency, and spectral requirements.

Figure 1: Remote Sensing and GIS in Precision Agronomy

2.2 GIS Fundamentals

GIS is a computer-based system designed to capture, store, manipulate, analyze, and display spatial or geographic data. It enables the integration of diverse datasets such as soil maps, topography, weather data, crop performance records, and remote sensing imagery. GIS supports spatial analysis techniques including overlay, buffering, interpolation, and spatial statistics, facilitating the generation of thematic maps and decision support tools. Georeferencing ensures spatial alignment of various datasets, allowing precise mapping of field variability and management zones.

2.3 Data Integration and Management

Effective precision agronomy requires seamless integration of remote sensing data into GIS platforms. Data preprocessing steps include radiometric calibration, atmospheric correction, geometric correction, and image classification. Temporal data series enable monitoring crop growth dynamics and detecting anomalies. Data management systems within GIS facilitate large dataset storage and retrieval, supporting real-time or near-real-time decision-making.

3. Applications of Remote Sensing and GIS in Precision Agronomy

3.1 Crop Monitoring and Health Assessment

Remote sensing-derived vegetation indices such as the Normalized Difference Vegetation Index (NDVI), Enhanced Vegetation Index (EVI), Soil-Adjusted Vegetation Index (SAVI), and Photochemical Reflectance Index (PRI) quantify crop vigor, biomass, chlorophyll content, and stress. Time-series analysis of these indices allows tracking of phenological stages, early detection of nutrient deficiencies, water stress, and pest or disease outbreaks. GIS-based spatial analysis maps intra-field variability in crop health, enabling targeted interventions. Multispectral and hyperspectral data enhance discrimination of subtle stress symptoms, improving management precision.

3.2 Soil Mapping and Characterization

Remote sensing technologies assist in mapping soil properties critical for precision agronomy. Hyperspectral imagery can identify soil organic matter content, texture classes, salinity, and moisture levels through spectral reflectance patterns. Thermal infrared data provide soil temperature profiles relevant to seedbed conditions. GIS integrates these datasets with conventional soil survey data to produce detailed soil property maps at field or landscape scales. These maps inform variable rate application of fertilizers, lime, and amendments, contributing to improved nutrient use efficiency and soil health.

3.3 Nutrient and Fertilizer Management

Spectral signatures derived from remote sensing can detect nutrient deficiencies by identifying characteristic changes in leaf reflectance associated with chlorophyll content and pigment composition. Early diagnosis enables timely nutrient supplementation. GIS-based nutrient management systems combine soil fertility maps, crop growth data, and yield history to develop prescription maps for variable rate fertilizer application. This spatially explicit approach reduces over-application, lowers costs, and minimizes environmental impacts.

3.4 Irrigation Scheduling and Water Management

Thermal infrared remote sensing provides canopy temperature data, which correlate with plant water stress levels. Elevated canopy temperatures indicate transpiration reduction due to water deficit. Soil moisture estimation is enhanced by microwave remote sensing and proximal soil moisture sensors. GIS integrates these data with weather information and crop water requirements to optimize irrigation scheduling. Decision support systems leverage this integrated information to recommend irrigation timing and volumes, enhancing water use efficiency and conserving scarce water resources.

3.5 Pest and Disease Detection

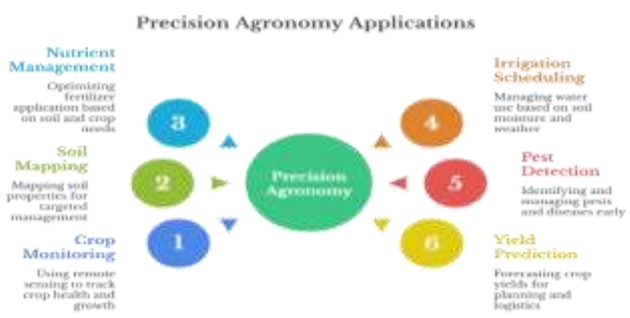
Remote sensing detects early pest and disease outbreaks by identifying spectral anomalies in crop

ISSN: 3049-2289

canopies caused by stress-induced changes in pigment composition and leaf structure. Hyperspectral and multispectral data facilitate differentiation of specific stress types. GIS maps the spatial extent and progression of infestations, enabling precision application of pesticides and targeted scouting. Early detection reduces chemical use, lowers production costs, and mitigates yield losses.

3.6 Yield Prediction and Mapping

Vegetation indices and biophysical parameters derived from remote sensing correlate strongly with biomass accumulation and yield potential. Time-series RS data combined with weather and soil information support yield forecasting models. GIS integrates historical yield data with these inputs to generate yield prediction maps, assisting in harvest planning, logistics, and market supply chain management. Precision yield mapping also enables feedback for adaptive management in subsequent seasons.



4. Data Sources and Platforms

4.1 Satellite Platforms

Satellite remote sensing provides large-area coverage with varying spatial, spectral, and temporal resolutions. Moderate-resolution satellites like Landsat (30 m spatial resolution, 16-day revisit) and Sentinel-2 (10-20 m, 5-day revisit) offer free multispectral data suitable for regional and field-level monitoring. Moderate to high-resolution commercial satellites (e.g., WorldView, PlanetScope) provide sub-meter imagery but at higher costs. Thermal and radar satellites (e.g., MODIS, Sentinel-1) support soil moisture and temperature monitoring.

4.2 Unmanned Aerial Vehicles (UAVs)

UAVs equipped with multispectral, hyperspectral, thermal, and RGB cameras provide ultra-high spatial and temporal resolution data. Their flexibility allows targeted monitoring of specific fields or problem areas, enabling rapid response. UAVs are particularly useful for small to medium-sized farms, research trials, and precision scouting.

4.3 Proximal Sensors

Ground-based sensors mounted on tractors, handheld devices, or stationary platforms collect real-time data on soil electrical conductivity, crop reflectance, chlorophyll fluorescence, and moisture. These data complement remote sensing and provide high precision for site-specific management.

4.4 GIS Software and Platforms

GIS platforms such as ArcGIS, QGIS, GRASS GIS, and specialized agricultural decision support systems provide tools for spatial data processing, analysis, and visualization. Cloud-based GIS and web mapping services facilitate data sharing and collaborative decision-making.

Table 1: Remote Sensing Platforms and Their Applications

Platform Type	Examples	Resolution Level	Applications in Agriculture
Satellite	Landsat, Sentinel	Moderate	Crop monitoring, NDVI mapping
UAV (Drones)	Multirotor, Fixed-wing	High	Field-level analysis, pest

			detection
Aircraft	Manned aerial systems	High	Large-scale surveys
Ground Sensors	Proximal sensors	Very High	Soil and crop parameter measurement

5. Integration of Remote Sensing and GIS with Precision Agronomy Technologies

5.1 Variable Rate Technology (VRT) Remote sensing and GIS data generate prescription maps that guide VRT-enabled machinery for site-specific application of fertilizers, pesticides, and irrigation. This technology optimizes input use by matching application rates to spatial variability in crop and soil conditions.

5.2 Decision Support Systems (DSS) GIS-based DSS integrate remote sensing data, weather forecasts, crop models, and expert knowledge to provide actionable recommendations. These systems support nutrient management, irrigation scheduling, pest control, and harvest planning.

5.3 Big Data and Machine Learning The integration of large volumes of RS and GIS data with machine learning algorithms enables advanced pattern recognition, anomaly detection, and predictive modeling. These techniques improve the accuracy and timeliness of agronomic decisions.

5.4 Internet of Things (IoT) IoT devices provide continuous real-time monitoring of environmental and crop parameters. When integrated with RS and GIS data, IoT enhances dynamic management and automation in precision agronomy.

6. Benefits of Using Remote Sensing and GIS in Precision Agronomy

a) **Enhanced Resource Use Efficiency:** Targeted input application reduces waste of fertilizers, water, and pesticides, lowering costs and environmental impacts.

b) **Improved Crop Productivity:** Timely detection of stress and spatial variability supports interventions that optimize growth conditions and yields.

c) **Environmental Sustainability:** Reduced chemical runoff and water consumption mitigate pollution and conserve natural resources.

d) **Cost Savings:** Optimized input use lowers production costs and increases profitability.

e) **Scalable Monitoring:** Remote sensing enables efficient monitoring of large and remote areas, supporting regional agricultural management.

f) **Data-Driven Decision Making:** Integration of spatial data improves the precision and confidence of management decisions.

7. Challenges and Limitations

a) **Data Resolution and Frequency:** Trade-offs between spatial, spectral, and temporal resolutions affect data suitability. High-resolution data may be costly or infrequently available.

b) **Cloud Cover and Weather Conditions:** Optical remote sensing is limited by atmospheric conditions, affecting data acquisition in cloudy or rainy periods.

c) **Complexity of Data Processing:** Effective interpretation requires expertise in remote sensing, GIS, and agronomy, which may be lacking in some regions.

d) **High Initial Investment:** Costs of sensors, software, hardware, and training can be barriers, especially for smallholder farmers.

e) **Integration Challenges:** Combining heterogeneous data sources and agronomic knowledge into coherent decision frameworks is complex.

f) **Data Accuracy and Validation:** Ground truthing and calibration are necessary to ensure the reliability of remote sensing-derived information.

8. Recent Advances and Future Directions

8.1 Hyperspectral Imaging

Advances in hyperspectral sensors provide detailed spectral information, allowing precise discrimination of crop species, nutrient status, and stress factors.

8.2 Thermal and Microwave Remote Sensing

Improved thermal sensors enhance monitoring of plant water stress and soil temperature, while radar and microwave sensors provide all-weather soil moisture data.

8.3 Cloud Computing and Big Data Analytics

Cloud platforms facilitate processing of large remote sensing datasets, enabling near real-time analytics and decision support.

8.4 Artificial Intelligence (AI) and Deep Learning

AI algorithms improve image classification, anomaly detection, and predictive modeling, increasing the accuracy and efficiency of RS and GIS applications.

8.5 Multi-Sensor Data Fusion

Combining optical, thermal, and radar data enhances information reliability and overcomes limitations of individual sensors.

8.6 Mobile GIS Applications

Mobile platforms enable field-level data collection, visualization, and decision support, enhancing farmer engagement and responsiveness.

8.7 Policy and Extension Integration

Training programs, subsidies, and knowledge-sharing networks promote adoption and effective use of RS and GIS technologies in precision agronomy.

9. Enhanced Data Analytics and Decision-Making Frameworks

The integration of remote sensing (RS) and Geographic Information Systems (GIS) in precision agronomy has catalyzed the development of advanced data analytics and decision-making frameworks. These frameworks leverage spatially explicit data to support complex agronomic decisions, enabling dynamic management of crops and resources.

a) **Spatial Variability Analysis:** GIS-based tools analyze intra-field variability by integrating multisource RS data, enabling identification of zones with differing soil fertility, moisture, or crop health status. This spatial differentiation supports targeted management practices.

b) **Predictive Modeling:** Combining RS-derived vegetation indices, soil properties, and weather data, predictive models forecast crop growth, yield potential, and stress events. Machine learning algorithms enhance model accuracy by capturing nonlinear relationships and temporal dynamics.

c) **Risk Assessment and Management:** GIS facilitates spatial risk mapping for abiotic stresses (drought, salinity) and biotic threats (pests, diseases) by integrating RS indicators with historical and environmental data. This supports proactive mitigation and resource allocation.

d) **Scenario Analysis and Optimization:** Decision support systems (DSS) use GIS platforms to simulate management scenarios, optimizing input application rates, irrigation schedules, and harvest

e) timing. Multi-criteria optimization balances productivity, cost, and environmental objectives.

f) **Real-Time Monitoring and Feedback Loops:** Integration of RS, GIS, and IoT enables near real-time monitoring of crop and soil conditions. Feedback loops allow adaptive management, adjusting practices promptly in response to observed changes.

g) **Spatial Data Visualization:** Advanced GIS visualization tools, including 3D mapping and interactive dashboards, enhance stakeholder understanding and facilitate communication of complex spatial information.

h) **Integration with Socioeconomic Data:** Incorporating farm management, market, and policy data into GIS enriches decision-making by contextualizing biophysical information within economic and social frameworks.

10. Conclusion

Remote sensing and GIS are transformative tools in precision agronomy, enabling site-specific management that enhances crop productivity, resource efficiency, and environmental sustainability. Their integration with emerging technologies such as artificial intelligence, IoT, and big data analytics promises to further advance precision agriculture. Overcoming challenges related to data accessibility, cost, and technical expertise will be critical to widespread adoption. Continued research, capacity building, and policy support are essential to fully realize the potential of remote sensing and GIS in precision agronomy.

References

Brisco, B., Brown, R. J., Hirose, T., McNairn, H., & Staenz, K. (1998). Precision agriculture and the role of remote sensing: a review. *Canadian Journal of Remote Sensing*, *24*(3), 315-327.

Liaghat, S., & Balasundram, S. K. (2010). A review: The role of remote sensing in precision agriculture. *American journal of agricultural and biological sciences*, *5*(1), 50-55.

Sahu, B., Chatterjee, S., Mukherjee, S., & Sharma, C. (2019). Tools of precision agriculture: A review. *Int. J. Chem. Stud*, *7*(6), 2692-2697.

Seelan, S. K., Laguette, S., Casady, G. M., & Seielstad, G. A. (2003). Remote sensing applications for precision agriculture: A learning community approach. *Remote sensing of environment*, *88*(1-2), 157-169.

Sishodia, R. P., Ray, R. L., & Singh, S. K. (2020). Applications of remote sensing in precision agriculture: A review. *Remote sensing*, *12*(19), 3136.

Call for Articles for Next Issue

Agriculture Bulletin
A Monthly Publication on Agriculture Trends
ISSN: 3049-2289

Agriculture Bulletin, a monthly publication on agriculture trends, is now accepting submissions for upcoming edition. We invite ***popular articles, case studies, opinion, reviews, and latest innovation updates*** *from researchers, professionals, and enthusiasts in the field.*

Important Dates

Submission Deadline: **25 April 2026**

Publication Date: **30 April 2026**

Submission Details

- Submit your article according to our guidelines by visiting: www.agriculturebulletin.in