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IR SPECTROSCOPY AND NANOTECHNOLOGY: A NEW LENS INTO THE INVISIBLE WORLD

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Abstract

Nanotechnology focuses on materials at the nanoscale, where conventional analytical techniques often fail to provide detailed chemical insight. Infrared spectroscopy, especially Fourier Transform Infrared Spectroscopy, offers a non-destructive method for probing molecular structure through characteristic vibrational fingerprints arising from stretching and bending modes. FTIR enables rapid, sensitive analysis with minimal sample preparation and broad applicability, making it well suited for nanoscience. Its applications include nanomaterial characterization, environmental and soil studies, biomedical and pharmaceutical analysis, and catalytic and industrial processes. Ongoing advances such as portable instruments, automation, and AI-assisted spectral interpretation continue to enhance the accessibility and impact of IR spectroscopy in revealing molecular-level information at the nanoscale.

Keywords: Fourier Transform Infrared Spectroscopy, Molecular Vibrational Analysis, Nanotechnology, Infrared Spectroscopy

Introduction: When Molecules Become Messages

In recent years, nanotechnology has transformed from an emerging scientific curiosity into a mainstream field influencing medicine, agriculture, materials science, and environmental research. Yet, studying matter at the nanoscale — where particles measure less than 100 nanometers — is far from simple. These particles are too small to examine with conventional optical microscopes, too complex to understand through basic chemical tests, and often too reactive to handle casually.

This is where Infrared (IR) spectroscopy, especially in its advanced form known as Fourier Transform Infrared Spectroscopy (FTIR), becomes invaluable. IR spectroscopy gives scientists a way to analyze the vibrations of atoms and molecules, extracting chemical information without destroying the sample. In nanotechnology research — including soil science, material engineering, food technology, and biomedical innovation — IR spectroscopy has become one of the essential tools for material characterization.

Understanding IR Spectroscopy: The Science of Vibrations

All molecules vibrate. Even when they appear still, atoms within chemical bonds are constantly stretching, twisting, or bending. When infrared light interacts with matter, bonds absorb specific wavelengths based on their movement. These absorption patterns form a unique spectral fingerprint, which scientists use to identify unknown substances, confirm compositions, and detect functional groups.

Types of Molecular Vibrations

Vibrations fall into two major categories: stretching and bending.

1. Stretching Vibrations

Stretching refers to a vibration in which the distance between atoms changes while remaining along the same bond axis. This occurs in two forms:

- **Symmetric Stretching:** Both atoms bonded to a central atom move in the same direction.
- **Asymmetric Stretching:** One atom moves closer to the central atom while the other moves away.

These stretching patterns are often responsible for major peaks in IR spectra and help identify key chemical structures, including C–H, O–H, N–H, and C=O bonds.

2. Bending Vibrations

Bending vibrations involve changes in the angle between bonded atoms rather than the bond length. These include:

- **Scissoring:** Atoms move toward or away from each other like scissors.
- **Rocking:** Atoms move together in the same direction within a plane.
- **Wagging:** Atoms move up and down out of the molecular plane.
- **Twisting:** One atom moves upward while the other moves downward.

These subtle vibration types help distinguish similar molecules or detect structural modifications — a critical requirement in nanoscience.

Fourier Transform Infrared Spectroscopy (FTIR): Precision Meets Speed

Earlier IR spectrometers analyzed one wavelength at a time, resulting in slow and sometimes inaccurate scans. FTIR revolutionized the process using a mathematical algorithm (the Fourier Transform), enabling simultaneous analysis of all infrared wavelengths.

Key advantages of FTIR include:

- Rapid spectral acquisition
- Higher sensitivity and resolution
- Ability to analyze solids, liquids, and gases
- Minimal or no sample preparation
- Compatibility with nanoparticles, thin films, and coatings



Applications in Nanotechnology

IR and FTIR spectroscopy are now widely used in multiple areas of nanoscience:

1. Characterizing Nanomaterials

Nanoparticles often contain functional coatings or engineered surfaces. IR spectroscopy identifies:

- Surface groups
- Oxidation changes
- Adsorbed molecules
- Chemical coatings

2. Soil and Environmental Nanoscience

Naturally occurring and engineered nanoparticles are present in soil. Applications include:

- Tracking pollutant interactions

- Understanding organic matter structure
- Studying mineral–nanoparticle reactions
- Monitoring soil amendments and fertilizers

3. Biomedical and Pharmaceutical Uses

IR spectroscopy assists in:

- Verifying drug–nanocarrier interactions
- Studying biomolecular changes
- Ensuring nanoparticle purity and stability

4. Catalysis and Industrial Engineering

Nanoparticles often act as catalysts due to their large surface area. IR spectroscopy helps monitor:

- Reaction intermediates
- Surface bonding changes
- Conversion efficiency

Future Outlook: Smaller Devices, Smarter Analysis

The future of infrared spectroscopy is moving toward smaller, smarter, and more efficient analytical systems. Next-generation developments are expected to include portable handheld FTIR instruments, enabling on-site and field-based analysis, along with artificial intelligence–assisted spectral interpretation to improve accuracy and speed of data analysis. Advances in real-time diagnostic capabilities are anticipated to support rapid environmental monitoring and medical applications, while fully automated quality control systems will enhance consistency and reliability in industrial settings. Together, these innovations will make IR spectroscopy faster, more accessible, and highly precise, extending its use well beyond traditional laboratory environments.

Conclusion

Infrared spectroscopy especially FTIR, stands as one of the most powerful tools in nanotechnology research. By allowing scientists to detect and interpret molecular vibrations, it provides a window into the nanoscale world that is otherwise invisible. Its applications continue to expand, influencing environmental science, medicine, engineering, and agriculture. As research progresses, IR spectroscopy is expected to remain a cornerstone technique — bridging the gap between observation and understanding in the microscopic and nanoscopic realms.

NANOPARTICLES IN ANIMAL FEED: NOVEL SUPPLEMENTS FOR IMPROVING HEALTH AND PRODUCTIVITY

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Abstract

Recent advances in nanotechnology have opened new avenues in animal nutrition and livestock management. Nanoparticles, defined as materials with dimensions typically between 1 and 100 nanometers, are gaining attention as innovative feed supplements due to their superior physicochemical properties. Their incorporation into animal diets has shown promising outcomes in terms of improved nutrient utilization, enhanced growth performance, strengthened immune responses, and better overall animal health. Various nanoparticles, including nano-selenium, nano-zinc, nano-copper, and silver nanoparticles, are being evaluated for their functional roles in livestock feeding systems. These nano-based supplements facilitate targeted nutrient delivery, minimize nutrient losses, and improve resistance to diseases. Applications across poultry, dairy, swine, and aquaculture sectors highlight the potential of nanotechnology to support efficient, sustainable, and high-yielding animal production systems capable of meeting the growing global demand for animal-derived foods.

Keywords: Nanoparticles, Animal Nutrition, Feed Supplements, Bioavailability, Sustainable Livestock Production

Introduction

Enhancing animal health and productivity has always been a primary objective of modern livestock production, driving continuous innovation in feed formulation and supplementation strategies. Conventional mineral and nutrient supplements are often associated with drawbacks such as low absorption efficiency, chemical instability, and excessive excretion, which not only reduce feed efficiency but also contribute to environmental contamination.

Nanotechnology offers a transformative solution to these challenges. Owing to their extremely small size and large surface-area-to-volume ratio, nanoparticles exhibit unique biological interactions that can be harnessed for improved nutrient delivery. When incorporated into animal feed, nanoparticles can serve as efficient carriers for minerals, vitamins, antibiotics, and vaccines, ensuring better solubility, stability, and site-specific release within the gastrointestinal tract. This article examines the growing role of nanoparticle-based feed supplements and discusses their advantages and applications in contemporary animal husbandry.

Types and Scientific Basis of Nanoparticles in Animal Nutrition

The effectiveness of nanoparticles in animal nutrition is primarily attributed to their nanoscale size (1–100 nm), which allows enhanced interaction with biological membranes and tissues. Both inorganic and organic nanoparticles are currently under investigation for feed applications.

Mineral Nanoparticles: Nano-sized forms of essential trace minerals such as zinc oxide, selenium, copper, and iron demonstrate superior bioavailability compared to their conventional counterparts.

Their improved solubility and absorption efficiency result in better mineral status at lower inclusion levels.

Silver Nanoparticles (AgNPs): Silver nanoparticles are widely recognized for their strong antimicrobial and antifungal activity. In animal feeding, they are explored for controlling pathogenic microorganisms in the gut, thereby improving intestinal health and reducing dependence on routine antibiotic supplementation.

Lipid-Based and Polymeric Nanoparticles: These nanoparticles function as advanced delivery systems for fat-soluble vitamins, probiotics, enzymes, and therapeutic agents. They protect sensitive compounds from degradation in the digestive tract and enable controlled or targeted release at specific sites.

Mechanisms of Action and Key Benefits

The shift from conventional supplements to nano-based formulations provides multiple advantages rooted in improved biological efficiency.

Improved Bioavailability and Retention: Nanoparticles are readily absorbed through intestinal epithelial cells, leading to higher systemic availability even at reduced dietary doses. This enhances nutrient retention and minimizes wastage.

Enhanced Growth Performance and Product Quality: Studies in poultry and swine have demonstrated improvements in feed conversion efficiency, average daily weight gain, carcass traits, and product quality parameters such as eggshell strength and meat composition following nano-mineral supplementation.

Augmented Immune Response and Antioxidant Defense: Nano-selenium and nano-zinc play a significant role in strengthening antioxidant defense systems by increasing the activity of enzymes like glutathione peroxidase. This reduces oxidative stress and improves disease resistance.

Environmental Sustainability: Higher absorption efficiency results in lower mineral excretion through manure, thereby reducing soil and water contamination with heavy metals and supporting environmentally sustainable livestock production.

Targeted Nutrient Delivery and Gut Health Improvement: Certain nanoparticles are engineered to release their active components under specific gastrointestinal conditions. Additionally, antimicrobial nanoparticles help suppress harmful bacteria such as *Escherichia coli* and *Salmonella*, fostering a healthier gut microbiome.

Applications in Different Livestock Sectors

Poultry Production: Nano-zinc and nano-selenium supplementation has consistently been associated with improved feed efficiency, egg production, eggshell quality, and enhanced immune responses against common viral diseases.

Dairy Farming: The inclusion of nano-minerals such as zinc, copper, and chromium in dairy rations has been linked to increased milk yield, improved milk composition, and reduced somatic cell counts, indicating better udder health.

Swine Industry: In pigs, nano-supplements enhance nutrient digestibility, improve intestinal morphology, and promote stronger skeletal development. These effects are particularly beneficial during the post-weaning period and in finishing pigs.

Aquaculture: Nanoparticle-based encapsulation techniques improve the stability and bioavailability of nutrients, vaccines, and immunostimulants in aquatic environments, leading to better growth performance, feed utilization, and disease resistance in fish and shrimp.

Table 1: comparative bioavailability and effect of conventional vs. Nano-form mineral sources in broiler chickens

Mineral source	Inclusion level (mg/kg diet)	Bioavailability index	Key observed effect (vs. control)	Reference
Zinc sulfate (conventional)	80	1.00	Improved weight gain	Wang et al., 2020
Zinc Oxide NPs	40	1.8-2.2	Superior weight gain and feed efficiency: lower excretion	Zhao et al., 2021
Sodium Selenite (conventional)	0.3	1.00	Increased serum Se levels	Zhao et al., 2021
Selenium NPs	0.3	1.5-2.0	Higher serum Se; enhanced antioxidant enzyme activity	Zhao et al., 2021

Conclusion

Nanoparticles are emerging as an exciting innovation in animal feeding, offering practical solutions to many long-standing challenges in livestock production. Because of their extremely small size, these particles allow nutrients to be absorbed more efficiently, helping animals grow better, stay healthier, and use feed more effectively. Nano-based supplements can strengthen immunity, improve gut health, and reduce nutrient wastage, which in turn lowers environmental pollution from animal waste. An added advantage is their ability to support disease control and reduce the routine use of antibiotics, making animal production safer and more sustainable. Although research is still ongoing to fully understand long-term safety and cost effectiveness, the results so far are highly encouraging. With proper regulation and responsible use, nanoparticles have the potential to become an important part of modern animal nutrition, supporting productive, healthy, and environmentally friendly livestock systems for the future.

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TRACEABILITY, TRANSPARENCY, AND FOOD SAFETY: RE-INVENTING TRUST IN THE GLOBAL FOOD SUPPLY CHAIN

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Abstract

Traceability and transparency have become most important in the current global food system when dealing with managing food safety. The supply chains are more intricate, food frauds occur frequently, and people desire to hear about the origin and morality of their food. This poses as a necessity of having sound tracking systems. Traceability refers to the practise of recording all the processes involved in food production and distribution, from beginning to the end. This is useful in recalling the items fast and also in imposing responsibility in the event of contamination or use of fake ingredients. With the help of transparency, consumers are likely to trust the system because this data is easy to find and check. To address how food traceability and transparency can be better, this paper studies various technologies, including blockchain, IoT (Internet of Things), AI (Artificial Intelligence), and smart packaging. Such technological advances enable a watch on the items in real-time, making decisions, and recording in inalterable databases, thus enhancing stronger food safety systems. Regulations such as the Food Safety Modernisation Act (FSMA) in the U.S. and efforts being made by the Food Safety and Standards Authority of India (FSSAI) are discussed to demonstrate the shift towards using digital tracking systems across the world. Issues such as integration between various systems, the financial implications of installing the systems, data security, and the disparity between the tech users and the users of that technology are also discussed in this paper, which impacts the small producer. The future is all-digital supply chains through the use of AI, which rests on data-driven predictions, and consumer-friendly apps that enhance transparency. In conclusion, this paper showcases the traceability and transparency as vital tools in ensuring the safety of food, establishing consumer confidence, and in the process of supporting food systems that can be sustainable across the globe.

Keywords: Traceability, Transparency, Blockchain, Internet of Things (IoT), Artificial Intelligence (AI), Smart packaging, Supply chain, Consumer trust, Digitalisation.

Introduction

In the 21st Century, food safety is a large healthcare concern all over the world. The production and distribution of food has transcended localities and established its own supply chains that are lengthy and complicated, with numerous stakeholders involved, such as farmers, processors, distributors, wholesalers, and retailers. It is in light of this that the governments, regulators, and industries find it a simple task to ensure the food that consumers receive is safe, authentic, and traceable.

Traceability refers to the possibility of tracking food products in terms of the entire manufacturing, food processing, and delivery process. Transparency accompanies this concept by ensuring that information on these steps, like the origin of data, its treatment, storage, and safety regulations, can be retrieved and verified by the consumers and other participants. All these combined helps to make the food safety systems more complex and enhance the level of trust between the producer and the

consumer. This has made traceability more significant due to food safety issues and the occurrence of fake food occurring across the globe. The 2008 melamine crisis in China, which was presented in the milk, and the 2013 horse meat crisis in Europe, which featured incorrect labels, illustrated the extent to which loose tracking systems are practised, resulting in massive public health problems and a lack of consumer confidence. According to the World Health Organisation (WHO), unsafe food triggers approximately 600 million diseases and 420,000 deaths annually [1]. These figures indicate that there is a dire need to have stringent measures of monitoring food throughout the supply chain.

Due to the advent of Industry 4.0 technologies, traceability and transparency have been modified digitally. The use of such tools as blockchain, IoT (Internet of Things), AI (Artificial Intelligence), and smart packaging has transformed the ways data is gathered, stored, and distributed. Such technologies make it possible to track products in time, automate data records, and make all parts of the supply chain more transparent. These solutions are attracting a lot of funds to governments and companies, as they are aware that food safety cannot be ensured without transparency of reliable data. Here, we shall examine why traceability and transparency are gaining prominence in food systems, the key technologies that can be used to improve this, the issues in using those types of technologies, and the opportunities of having a safer and more sustainable international food system.



Figure 1. Graphical diagram of the food supply chain and traceability points.

The Requirement of Traceability and Transparency

Some of the reasons that are interconnected lead to the push in favour of traceable and transparent food systems, which ensure food safety, consumer trust, legal compliance, and sources that are obtained in an ethical fashion. In the modern food market around the world, a food item that is sold may contain ingredients from other continents. An example shall be the case of a packaged meal having spices of India, meat of Brazil, and packaging of Chinese origin. This complicates the issue of locating the cause of the problem in case there is a safety problem. The fact is that traceability implies that there is accountability throughout the chain of custody. It also allows regulators and manufacturers to easily detect bad batches and take them off the market, which reduces the risks to people's health. In the 2006 E. coli outbreak in spinach in the U.S., the lack of digital tracking systems implied that recalls took weeks. Those companies that eventually embraced blockchain-based tracking reduced replacement periods to less than five seconds. It is also essential to have transparency to create trust between the brand and the consumer.



Figure 2: 2006 E. coli O157:H7 outbreak linked to bagged spinach in the United States.

According to a report by the World Economic Forum (2021), more than 70% of global consumers are interested in learning more about how their products are produced, processed, and transported. Sustainability, fair trade, and animal welfare are other concerns to consumers, and this compels companies to share information about more than merely safety, such as carbon footprint, sourcing ethics, and labour practises. World regulations have given focus to these requirements. Regulation (EC) No 178/ 2002 requires traceability by the European Union, and it stipulates that every food operator should be aware of the origin of a product and its destination. The Food Safety and Standards Authority of India (FSSAI) has also put forth such requirements in India, particularly on dairy, seafood, and organic products that are exported to other countries. In short: traceability and transparency are to be boxes on compliance lists, but they are critical components of a food system that consumers can trust and which can withstand, as much as they desire, that is what they want of real food, food safety, and food responsibility.

Global Food Safety Challenges

Although scholars and corporations have been making considerable strides to enhance food security, food systems the world over are still experiencing numerous issues that are throwing a spanner in the health of the populace and the economy. These include microbes, chemicals, and physical dangers, and everything that gets in the way of the social, economic, and tech aspects. Biological dangers, such as bacteria (*Salmonella*, *Listeria monocytogenes*), viruses (*norovirus*, *hepatitis A*), and parasites that creep into food during preparation or processing, or even during storage. The suspects are usually poor temperature regulation, poor cleaning, and unsafe handling. Chemical dangers, like pesticides, heavy metals, or industrial residues, find their way into our food. Think of the melamine case of 2008 in China, when milk manufacturers put a nitrogen-rich substance into milk to appear more protein-rich. That was a textbook example of how a single chemical can damage thousands of infants.

The New York Times

China Begins Inquiry Into Tainted Baby Formula

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Chinese officials check powdered milk products at a supermarket in Zaozhuang, Shandong province on Friday.
Reuters

By [Keith Bradsher](#)
Sept. 12, 2008

Figure 3: News report excerpt highlighting the 2008 China milk adulteration scandal.

Food fraud has become a global problem due to money. European horse-meat scandal and the counterfeit cases of olive oil, honey, and spice are indicative of the poor performance of weak, old paper tracking systems. The real is becoming more difficult to distinguish from the fake. Tech and social issues, the main issue is the absence of digital technology, particularly in less developed nations, with many small farmers who are not linked to organised supply chains. These manufacturers normally lack access to contemporary equipment, the internet, or expertise in tracking their goods, leaving gaps in data that render the entire system vulnerable. FAO and WHO have indicated that an inaccurate location only slows down the response and increases the recall. In addition, importers at national boundaries desire to be assured of provenance and safety as the goods enter their countries, thus exporters should come with sound tracking processes. Dealing with these problems, all you need is technology upgrades, global coordination, policy alignment, and capability creation throughout the board.

Basic Technologies to Support Traceability and Transparency

The food industry has been digitising at a great pace to keep track of and remain transparent. In their place, smart technology to gather, store, and share information is emerging to modernise paper documents between all the members of the supply chain. The blockchain, IoT, AI, Big Data analytics, and smart packaging are the most useful techniques.

Blockchain Technology

Big data in terms of food traceability is the blockchain. It is a decentralised electronic registry that cannot be altered and connects all the processes in sequence; swapping data is almost impossible without consensus. This implies that the data is more reliable and the supply chain bunch develops more confidence. Regarding food, blockchain technology enables tracing of the whole supply chain, from farm to fork, through keeping track of all the pertinent connections in real time via QR codes and online entries. A nice illustration is the food trust platform by IBM that Walmart and Nestle use,

which is used to track the product in real-time. As the Chinese experiment conducted by Walmart showed, blockchain was capable of identifying the origin of a mango in 2.2 seconds, as opposed to the previous 7-day delay. The speed is not the only thing that the blockchain brings to the table: a scan of the product takes consumers immediately to the place of its cultivation, harvesting, shipping, etc. Fraud and mislabelling are reduced by the fact that the data cannot be easily altered.

The issue is that the implementation of blockchain demands repeated data input, a solid internet, and cooperation within the industry. Poor countries have small farmers who are not able to meet those requirements. Nevertheless, it is preferred due to the safety and trust benefits.

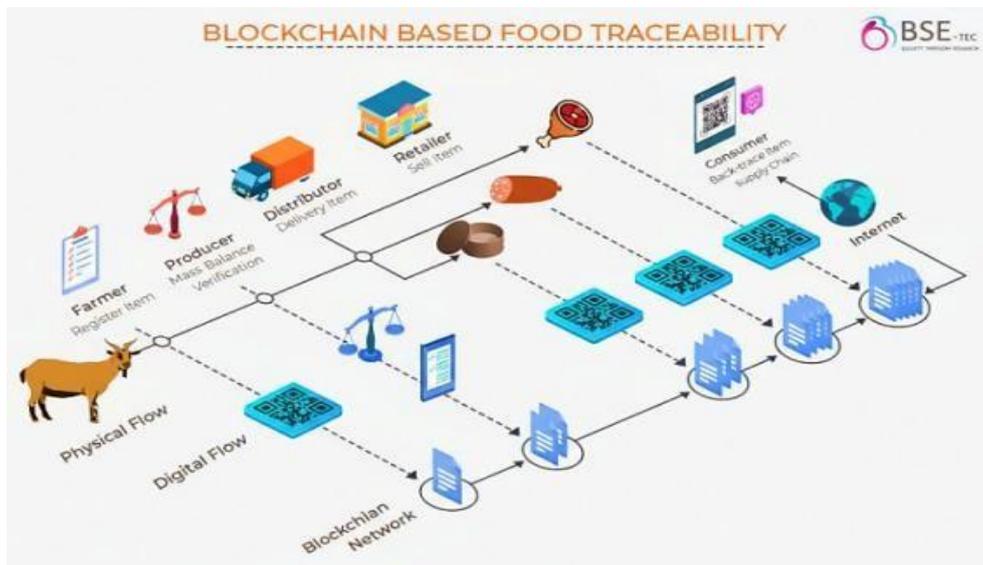


Figure 4: Blockchain model of storing and authentication of food traceability information.

Sensor-Based Systems and Internet of Things (IoT)

IoT consists of real-time communication maintained by the connected devices and sensors. These tools track some important parameters such as temperature, humidity, pH, and storing time- these parameters influence the safety and quality of food. An example would be an instance of shipping of seafood or dairy items that should remain cold, where the temperature results are sent to a database via IoT sensors. In case the temperature goes out of the safe range, an alert is displayed, and the operator can correct it immediately. Such systems also minimise spoilage, ensure everything is full of the regulations such as HACCP, and enhance traceability by associating physical objects to record data with RFID tags and NFC chips.

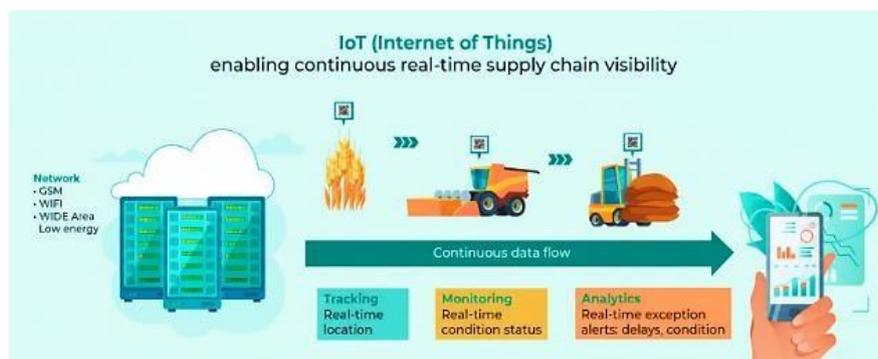


Figure 5: Application of IoT and sensors in real-time monitoring of food safety parameters.

Combining IoT and blockchain increases the intensity of all of that: IoT provides the actual data in real-time, and blockchain secures it in such a way that it is not possible to change. They create a transparent digital framework that increases consumer confidence and ensures we comply.



Figure 6: Working mechanism of RFID-based traceability in the food supply chain.

Big Data Analytics and Artificial Intelligence (AI)

The use of Artificial Intelligence (AI) and Big Data analytics is completely transforming the ways to visualise and make use of tracking data. All food production processes produce highly tuned data sensors and equipment on the farm for sales volumes. AI analyses such data in order to find trends, predict threats, and improve safety. As an example, machine learning can identify the early indicators of contamination or fake ingredients either through sensor readings or through ingredient makeup. It may also predict when equipment in food plants may malfunction and minimise the downtime as well as contamination.

Big Data analytics is also used to assist in decision-making through the integration of information from different sources, such as weather, shipping, and reviews made by consumers. The regulators are able to detect any problems more quickly, in addition to carrying out inspections more efficiently with the help of these tools. Businesses will be able to make their operations more transparent and build their brand. The key issue is that data consistency needs to take place, which refers to the fact that it should be applied by all people in terms of formats and systems. Nonetheless, food tracking with the help of AI and analytics is a significant jump into the proactive, data-driven management of food safety.

Smart Packaging and Digital Labelling

Smart packaging is simply such a blend of substances, sensors, and technology that spits out the real-time details of the actual freshness of a product. Consider Time-Temperature Indicators (TTIs), gas sensors, and biosensors; all of this is increasingly being used to monitor the progress of food as it makes its journey before it throws the switch and goes bad. An example is a TTI label on chicken, which turns colour to indicate whether it has been exposed to unsafe temperatures during shipping or not. Besides that, which is into that, a biosensor-packed package can actually pick bacteria and provide retailers or consumers with a visual signal of the bacteria detection, as demonstrated by colour shifts, or a notification.



Fig. 7: Schematic representation of a Time-Temperature Indicator (TTI) that is commonly used in smart food packaging to measure the freshness of the food.

Digital labels are combined with smart packaging, e.g., QR codes and RFID tags. They will work in tandem with smart packaging, allowing you to directly access product information. You may simply enter that code in your phone and directly know the origin of the food, when it was processed, when it had certifications, and whether it is sustainable. Such interactivity between producer and consumer simply clarifies the entire situation and makes things more responsible. Smart packaging essentially marks tracking to consumer awareness to ensure that safety information is not simply placed somewhere, but rather presented transparently.

Implementation of Traceability into Food Safety Management Systems

Monitoring should not seem like an independent showmanship; it belongs to larger food safety systems such as HACCP (Hazard Analysis and Critical Control Points), ISO 22000, and FSSC 22000. These frameworks are based on identifying crucial locations where hazards or contamination are intercepted in their course through monitoring and record keeping. Integrating tracking tools within these systems will ensure that the companies are certain that data gathering and corrective measures are automated and accurate, and that they can be audited. Online tracking systems are also able to record all the processes of the HACCP scheme, such as the ordering of raw materials until the delivery of complete products. That reduces the amount of paperwork and enhances accuracy. When a bad batch is detected, digital tracking will quickly identify the specific place of production or shipping line to reduce the amount of money as well as brand damage. In India, FSSAI

would like traceability to be part and parcel of food production and dairy, seafood, and organic export food industry to be among the key areas. The Foscos portal is entitled the Food Safety Compliance System (Foscos) portal, which provides companies with an opportunity to have all documents digitised and trace them all online, which clearly represents a shift in the direction of national traceability networks.

Challenges and Barriers to Implementation

Even with these problems, global changes show things are getting better. Groups like FAO, WHO, and Codex Alimentarius Commission are working on rules that work the same way so that tracking systems are widely seen and helpful. Although the ideal aspect of tracking and transparency is fantastic, a plethora of challenges prevent them from being implemented without any hitch:

- **Cost and Infrastructure Limit:** Blockchain or IoT systems cost money to install, to purchase hardware and software, and to hire well-trained workers. The small businesses, in many cases, are not able to invest or are not equipped with the necessary skills.
- **Data Fragmentation:** The various stakeholders tend to adopt different data formats and standards, and this impairs integration, which implies that it is hard to share data smoothly.
- **Lack of Cooperation:** Some producers and distributors are afraid of becoming known to the competitors or being heavily burdened by regulation, and thus will not be free to share.
- **Cybersecurity and Privacy:** Since such systems are based on digital data, they become the brunt of cyberattacks. The protection of sensitive information is vital to ensure trust.
- **Regulatory and Policy Gaps:** In most of the third world countries, food-tracking policies do not exist or are poorly implemented. Disparate rules result in unequal practises.

Though there are these challenges, international efforts, such as those of FAO, WHO, and Codex Alimentarius Commission, are going in the direction of harmonising guidelines, making tracking systems generally decentralised and efficient.

Future Perspectives

Going forward, there is a tendency to completely computerise it all making systems virtually self-operating and giving the consumer more power. Digital twins, edge computing, and synthetic biology tracking are some of the new technologies that are expected to completely transform food systems. We will have blockchain and artificial intelligence driving self verifying supply chains with each step. Virtual copies of food processes that represent digital twins will enable the stakeholders to foresee hazards and do simulations before the incidence of issues. Consumer apps will become more advanced, as well. Think of food passports on your phone and a digital labelling system that provides info on the safety, sustainability, and ethics of what you are eating in more detail. International cooperation will play a major role as well. Digital systems of producer, regulator, and retailer collaboration in the form of global tracking networks can be successful actions towards attaining the UN Sustainable Development Goals, particularly SDG 2 (Zero Hunger) and SDG 12 (Responsible Consumption and Production).

Conclusion

Tracking and transparency are more than a niche; they have become elements of food safety in the twenty-first century. With the growth of supply chains and the increasing demand of consumers to find out more about them, the industries are forced to implement new technologies to guarantee authenticity, responsibility, and trust. Such tools as blockchain, IoT, AI, and smart packaging play a key role in dynamizing old systems into new smart and interconnected networks. Nevertheless, their

success depends on their ability to match costs, regulations, and digital skills. In the case of countries such as India, adoption of such technologies will help increase the level of competitiveness of exports, improve food safety, and become consistent with sustainability globally. Simply put, tracking is not only about tracing food flow but also about instilling trust in the food that people eat, the systems creating that food, and the future of society's health.

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SEED QUALITY ASSURANCE SYSTEMS : A PILLAR OF MODERN CROP PRODUCTION

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Abstract

Seed quality assurance is a fundamental component of sustainable agricultural production, as seed performance directly influences crop establishment, yield stability and farmer profitability. This article highlights the concept and importance of seed quality assurance as a comprehensive system that safeguards genetic purity, physical quality, physiological vigour and seed health throughout the seed production and supply chain. Emphasis is placed on key quality components, including field inspection, laboratory testing, processing and scientific storage practices, which collectively ensure the delivery of reliable and high-performing seed to farmers. The article also discusses the benefits of effective seed quality assurance in enhancing productivity, reducing production risks and strengthening farmer confidence, while addressing existing challenges such as climatic variability and infrastructural limitations. Strengthening regulatory mechanisms, adopting advanced testing technologies and building technical capacity are identified as critical strategies for improving seed quality systems. Overall, the article underscores that seed quality assurance is not only a regulatory necessity but a strategic investment in achieving resilient, productive and sustainable agricultural systems.

Keywords: Seed Quality Assurance, Seed Certification, Field Inspection, Seed Testing and Quality Control.

Understanding Seed Quality Assurance

Seed quality assurance refers to a systematic process that ensures seeds meet prescribed standards of genetic purity, physical purity, physiological vigour and health before reaching farmers. It involves multiple stages from breeder seed development to certified seed production, processing, testing, storage and marketing. Each step is carefully monitored to maintain the integrity and performance of the seed.

Key Components of Seed Quality

- **Genetic Purity** : Genetic purity ensures that the seed belongs to the correct variety or hybrid and expresses its intended traits. Maintenance of isolation distance, controlled pollination, rouging of off-types and field inspections are essential practices to preserve varietal identity.
- **Physical Purity** : Physical purity refers to the absence of inert matter, weed seeds and seeds of other crops. Proper seed cleaning, grading, and processing help achieve high physical purity, which directly affects sowing efficiency and crop establishment.
- **Germination and Vigour** : Germination percentage indicates the seed's ability to sprout under favourable conditions, while seed vigour reflects performance under stressed

environments. Standard laboratory tests and vigour assessments ensure that only high-performing seed lots are approved for distribution.

- **Seed Health** : Seeds must be free from seed-borne diseases and pests. Health testing, seed treatment and proper storage conditions help prevent disease transmission and protect crop health during early growth stages.

Role of Field Inspection and Testing

Field inspection is a cornerstone of seed quality assurance. Regular inspections during critical crop stages help verify varietal purity, crop condition and compliance with certification standards. Post-harvest laboratory testing further validates germination, moisture content, purity and health parameters. Only seed lots that meet established standards are certified and labelled for sale.



Figure 1: Field inspection for quality seed production

Importance of Proper Processing and Storage

Seed processing enhances quality by removing contaminants and improving uniformity. Equally important is storage under controlled temperature and humidity to maintain viability and vigour until planting. Inadequate storage can rapidly deteriorate seed quality, even if production standards are met.

Benefits of Seed Quality Assurance

- Ensures uniform crop stand and higher productivity
- Reduces risk of crop failure and disease spread
- Builds farmer trust and confidence in seed brands
- Supports adoption of improved varieties and hybrids
- Contributes to national food security and agricultural sustainability

Challenges and Way Forward

Despite its importance, seed quality assurance faces challenges such as climatic variability, limited infrastructure and unorganized seed markets. Strengthening quality control systems, adopting advanced testing technologies, capacity building of seed professionals and creating farmer awareness are essential steps to overcome these challenges.

Conclusion

Seed quality assurance is not merely a regulatory requirement but a commitment to agricultural excellence. High-quality seed serves as the backbone of modern farming, enabling farmers to realize the full potential of improved varieties. By investing in robust seed quality assurance systems, the agricultural sector can ensure sustainable productivity, profitability and resilience for future generations.

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- Seed Quality and Certification Principles — Academic resources (e.g., crop improvement texts) describe key quality attributes such as genetic purity, physical purity, germination and seed health.

FROM EARTH TO PLATE: REIMAGINING JHIMIKAND AS THE ULTIMATE FUNCTIONAL FOOD

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Introduction

Jhimikand (*Amorphophallus paeoniifolius*), commonly known as “Elephant Foot Yam” (EFY) or locally as “suran” in many parts of India. This magnificent tuber, with its distinctively large corm, often solitary flower that gives it its name (from the greek “amorphos” meaning without form, and “phallos” referring to its spadix), is a powerhouse of nutrition and a cornerstone of food security for millions. Originating from Southeast Asia, EFY has spread across tropical and subtropical regions, finding a particularly strong foothold in India, Bangladesh, Sri Lanka, Philippines, Indonesia, and some parts of Africa. Its cultivation is especially prominent in marginal lands and rainfed areas, where its ability to thrive under challenging conditions makes it an invaluable asset to smallholder farmers. Despite its widespread presence and significant contributions to local economies and diets, jhimikand often takes a back position to more globally recognized tubers like potato or sweet potato.

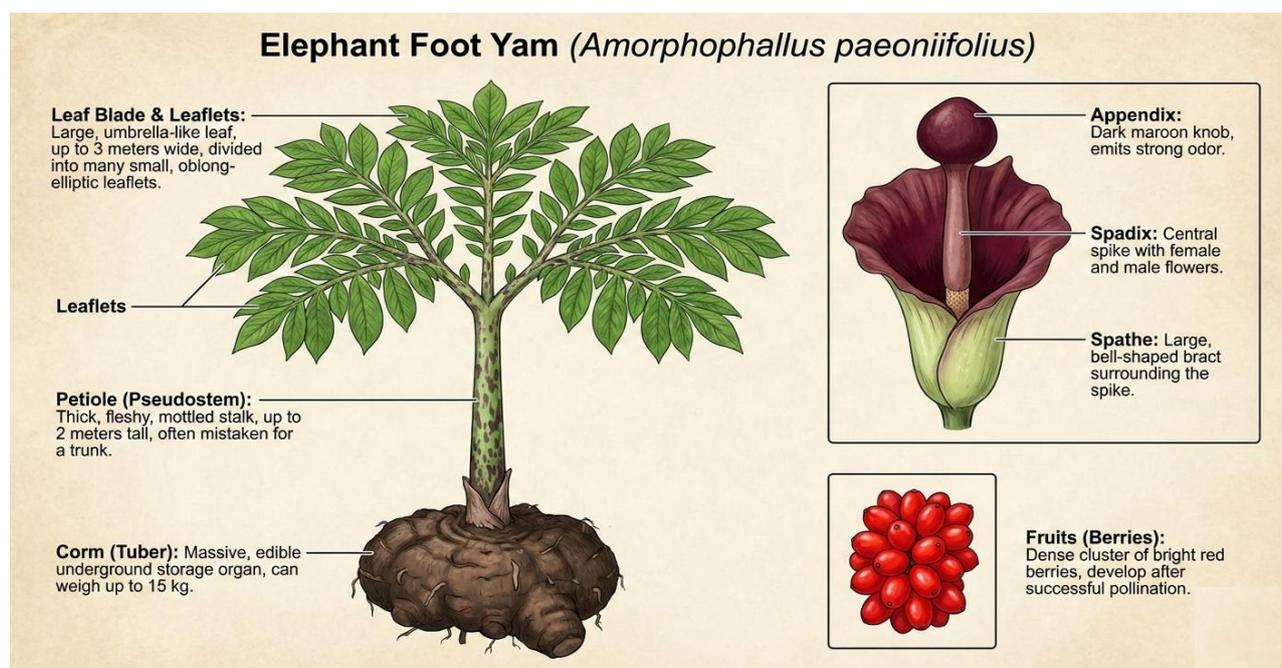
However, as the world goes with climate change, food security challenges, there is a need for diversified agricultural systems looking towards resilient and nutrient-dense crops like jhimikand. Its adaptability, ease of cultivation, high yield potential, and impressive nutritional profile position it as a “future-proof crop”, capable of addressing modern agricultural demands.

Botanical and Agronomic Overview

Amorphophallus paeoniifolius belongs to the Araceae family, is characterized by a large, underground corm (a swollen stem base) that serves as its primary storage organ, accumulating starch and other nutrients. This corm is the edible part of the plant, varying in size from a few hundred grams to several kilograms, often resembling an elephant’s foot due to its irregular shape and rough, brownish skin. The plant produces a single, large, highly dissected leaf that emerges from the corm. This leaf, often several meters tall, resembles a small tree, providing the photosynthetic engine for corm development. Before the leaf emerges, or sometimes alongside it, the plant produces a solitary, large, purplish-brown inflorescence (flower) that emits a strong,



pungent odor designed to attract pollinating insects, primarily flies. This unpleasant smell is a transient characteristic and does not affect the edibility of the corm. After a growing season, the leaf senesces, and the plant goes dormant, relying on the stored energy in its corm, ready to sprout again with the next rainy season. This dormancy period is crucial for corm development and maturation.



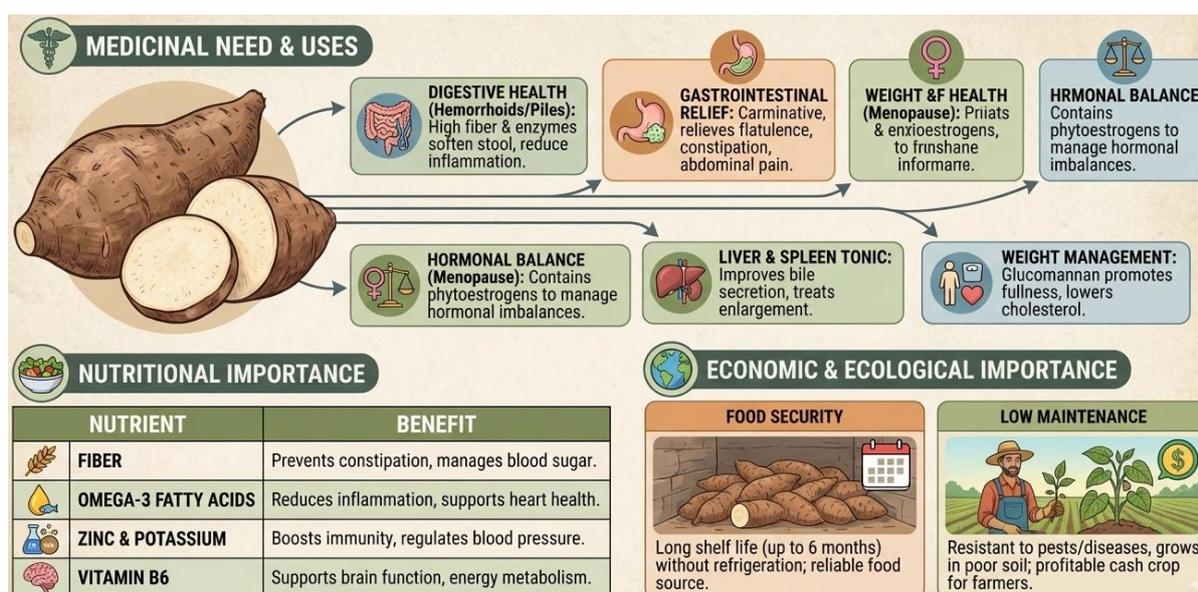
Jhimikand is a perennial crop, meaning it can be harvested and replanted from pieces of the corm for multiple seasons. Its long growth cycle, typically 7-9 months from planting to harvest, allows for significant biomass accumulation. The traditional cultivation method often involves planting cormels (small corms) or corm pieces in raised beds, allowing for good drainage and optimal corm development.

Nutrient Content

Jhimikand is a nutritional powerhouse *i.e.* offering a diverse array of macronutrients, micronutrients, and bioactive compounds that contribute significantly to human health. Its robust nutritional profile makes it an excellent choice for combating hidden hunger and diversifying diets.

- **Carbohydrates:** The primary component in jhimikand is carbohydrates, predominantly in the form of starch. This makes it an excellent energy-providing food, crucial for an active lifestyle. The complex carbohydrates in EFY are digested slowly, providing sustained energy release and helping to maintain stable blood sugar levels. This characteristic can be particularly beneficial for individuals managing diabetes.
- **Dietary fiber:** One of the most significant health benefits of jhimikand is its high dietary fiber content, with some sources reporting up to 5.7 g per 100 g of fresh tuber. Both the soluble and insoluble fibers are present. Soluble fiber helps to lower blood cholesterol levels, regulate blood sugar, and promote a feeling of fullness, aiding in weight management. Insoluble fiber adds bulk to stool, facilitating regular bowel movements and preventing constipation, thereby promoting gut health.

- **Protein and fat:** While not a primary source of protein, it contains a modest amount, with values ranging from 1.2 to 2.6 g per 100 g. Its fat content is very low, typically around 0.1 - 0.4 g per 100 g, making it a lean, healthy food choice.
- **Vitamins:** Jhimikand is a good source of several essential vitamins. It is particularly rich in Vitamin B6 (pyridoxine), which plays a crucial role in brain development and function, and the metabolism of proteins, fats, and carbohydrates. It also contains a good amount of Vitamin C (ascorbic acid), a powerful antioxidant vital for immune function, skin health, and wound healing. Other B vitamins, such as folate (B9) and thiamine (B1), are also present in varying amounts.
- **Minerals:** The mineral content of jhimikand is equally impressive. It is a significant source of potassium (upto 327.83 mg per 100 g), phosphorus (around 166.91 mg per 100 g), calcium (around 161.08 mg per 100 g), iron (upto 3.43 mg per 100 g) etc.
- **Phytochemicals and antioxidants:** Jhimikand is laden with various phytochemicals and antioxidant compounds, including phenolic compounds, flavonoids (like quercetin), and carotenoids. These compounds help neutralize free radicals in the body, reducing oxidative stress and potentially lowering the risk of chronic diseases such, as heart disease, certain cancers, and neurodegenerative disorders. The presence of a steroidal saponin, also adds to its medicinal value, being explored for its anti-inflammatory and cholesterol-lowering properties.
- **Anti-nutritional Factors and Acridity:** A notable characteristic of EFY is its acridity, which causes an itching sensation in the mouth and throat if not properly prepared. This is primarily due to the presence of calcium oxalate crystals (raphides). However, traditional cooking methods, such as boiling, frying, or pickling, often with tamarind or other acidic agents, effectively neutralize these compounds, making the corm perfectly safe and palatable.



Conclusion and future thrust

Jhimikand (EFY) offers a compelling blend of resilience, nutritional richness, and agricultural adaptability. It has sustained communities for centuries, providing an invaluable source of energy, vitamins, minerals, and dietary fiber. Its ability to thrive in marginal lands, resist drought to a significant extent, and yield abundantly under diverse conditions makes it an ideal crop for

sustainable agricultural systems, particularly in the face of escalating climate change. Beyond its agronomic merits, the impressive nutritional profile of EFY, contain complex carbohydrates, essential vitamins (B6, C, folate), and critical minerals (potassium, phosphorus, magnesium, calcium, iron, zinc), positions it as a powerful tool in combating malnutrition and promoting public health. Its unique phytochemicals further underscore its potential as a functional food with broader health benefits, including anti-inflammatory, antioxidant, and anti-diabetic properties. Increased research into improved varieties, enhanced cultivation practices, efficient post-harvest handling, and diverse processing methods can unlock its full potential, transforming it from an underutilized regional staple into a globally recognized superfood. Jhimikand is not just about cultivating a crop; it is about investing in food security, biodiversity, and the health of both people and the planet. As we navigate the complexities of modern agriculture, the unassuming EFY offers a powerful, resilient, and nutritious solution, ready to take its rightful place at the forefront of the global food system.

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DECODING THE GINGER RHIZOSPHERE : HOW SOIL MICROBIOME CHANGES REVEAL HIDDEN DISEASE THREATS

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Abstract: Ginger (*Zingiber officinale*) cultivation is increasingly threatened by soil-borne diseases such as bacterial wilt (*Ralstonia solanacearum*) and rhizome rot complexes, which often remain undetected until severe yield losses occur. Recent advances in rhizosphere microbiome research reveal that disease emergence is preceded by predictable shifts in soil microbial communities rather than sudden pathogen outbreaks. This article explores how rhizosphere dysbiosis characterized by reduced microbial diversity, loss of beneficial taxa, and functional imbalance serves as an early-warning signal of disease risk in ginger systems. Integrating high-throughput sequencing, metabolomics, and predictive diagnostics, microbiome-informed approaches offer new pathways for disease management, emphasizing soil health.

Keywords : Ginger, Rhizosphere microbiome, Soil-borne diseases, *Ralstonia solanacearum*, Bacterial wilt, Soil health

Introduction

Ginger (*Zingiber officinale*) is far more than a kitchen spice. It sustains millions of farmers across Asia, Africa, and Latin America and supports global food, pharmaceutical, and nutraceutical industries. Beneath ground lies a persistent and invisible threat: Soil-borne pathogens that quietly erode productivity long before symptoms appear above ground. The most destructive are *Ralstonia solanacearum* causes bacterial wilt and different rhizome rot complexes are some of the most harmful. Once established, these diseases can devastate entire fields and remain entrenched in soil for years, defying conventional control measures (Ahmed *et al.*, 2022; Cui *et al.*, 2024). For decades, growers and scientists relied on visible symptoms or pathogen isolation approaches that detect disease only after damage is already done.

Presently, research on the rhizosphere microbiome surrounding plant roots reveals that disease rarely strikes without warning. Instead, it is preceded by subtle but detectable shifts in microbial communities, long before plants begin to wilt.

“Soil-borne disease is not a sudden invasion; it is a slow ecological unravelling.”

Rhizosphere: A Living Interface Between Soil and Plant

The rhizosphere is a biologically active soil zone shaped by root exudates that structure microbial communities and regulate nutrient availability, pathogen suppression, and plant immunity (Berendsen *et al.*, 2012).

In healthy ginger soils, beneficial microbes form complex networks that limit pathogen establishment through competition, antimicrobial activity, niche occupation, and immune priming, a process known as natural disease suppression (Weller *et al.*, 2002).

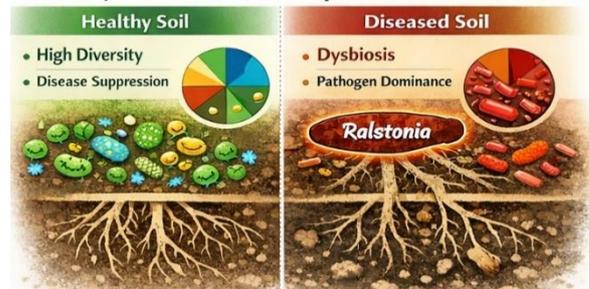
This balance is easily disrupted by monocropping, intensive chemical use, poor organic matter management, and environmental stress, creating conditions favorable for pathogen proliferation (Sun *et al.*, 2025).



Understanding Pathogen to Microbial Ecology

Traditional plant pathology targeted individual causal organisms, but microbiome research shows that pathogens establish only when the surrounding microbial community permits. Disease is therefore a community-level phenomenon. Healthy ginger rhizospheres are enriched with beneficial genera such as *Bacillus*, *Pseudomonas*, and *Streptomyces*, which produce antibiotics, siderophores, and lytic enzymes that suppress pathogens and enhance nutrient uptake and root growth (Wang *et al.*, 2025). Early microbial configurations can predict disease outcomes before pathogen proliferation.

Healthy vs. Diseased Rhizosphere



“Disease risk is written into microbial patterns long before symptoms appear.”

Early-Warning Signals

Disease follows a predictable ecological trajectory, beginning with gradual losses of beneficial microbes and shifts in microbial interactions rather than pathogen surges. In ginger soils, declines in antagonistic genera such as *Bacillus* and *Pseudomonas* occur weeks before visible wilting, acting as an early biological warning of instability (Wang *et al.*, 2025). These microbial patterns enable a transition from binary “disease or no disease” diagnostics to risk-based assessments, where shifts in community composition indicate whether soil conditions are trending toward or away from disease.

Timeline of Disease Development



Plants as Active Players: Root Exudates and Feedback Loops

Ginger roots actively shape their rhizosphere through exudation, modulating chemical outputs in response to nutrition, stress, and microbial interactions (Jones *et al.*, 2009). Under optimal conditions, exudates support beneficial microbes; under stress, they may inadvertently favor opportunistic or pathogenic organisms. Metabolomic analyses show that diseased ginger soils exhibit distinct chemical signatures, including altered organic acids and phenolics, closely linked to microbial restructuring (Wang *et al.*, 2025). These feedback loops amplify dysbiosis and disease progression, explaining why chemical control often fails, as it targets pathogens without restoring the underlying ecological balance.

Tools and Techniques for Decoding the Ginger Rhizosphere

- 1. Seeing the Invisible:** For decades, ginger soil-borne diseases were diagnosed using classical microbiological approaches, including symptom observation, pathogen isolation, and biochemical tests (Agrios, 2005). While foundational, these methods are inherently reactive, detecting disease only after pathogens have caused visible damage. In complex soils, where pathogens exist at low densities amid diverse microbial communities, such approaches provide an incomplete and delayed understanding of disease dynamics. Recognition that disease emerges from shifts in the microbial community highlights the need for tools capable of assessing entire soil microbiomes rather than individual pathogens.
- 2. Mapping Microbial Communities:** High-throughput sequencing of bacterial 16S rRNA and fungal ITS regions allow researchers to profile thousands of taxa simultaneously (Caporaso *et al.*, 2012). These reveal the microbial diversity in wilt-affected soils.
- 3. Shotgun Metagenomics:** Metagenomics also enables the identification of beneficial functions lost during disease development, including genes associated with antibiotic production, nutrient cycling, and induced systemic resistance (Berendsen *et al.*, 2012).
- 4. Chemical Conversations in the Soil:** By integrating metabolomic data with microbiome sequencing, researchers can reconstruct cause–effect relationships between root exudation, microbial metabolites shift, and disease development. This integrative approach moves diagnostics beyond correlation toward mechanistic insight, revealing how chemical environments shape microbial outcomes (Jones *et al.*, 2009; Wang *et al.*, 2025).
- 5. Quantitative PCR and Targeted Molecular Diagnostics:** Quantitative PCR remains essential for confirming *Ralstonia* presence, but newer strategies target indicator microbes and functional genes that reflect overall soil health (Mumford *et al.*, 2016). This shift allows qPCR to function not merely as a detection tool but as a risk assessment instrument, signalling when rhizosphere conditions favour disease even if pathogen levels remain low. Such targeted diagnostics are faster, cheaper, and more adaptable to routine monitoring than full-scale sequencing.
- 6. Machine Learning and Predictive Microbiome Models:** The large volume of microbiome data has driven the use of machine learning and AI to detect predictive patterns beyond traditional statistics. By training algorithms on microbial community profiles linked to disease outcomes, models can forecast disease risk with high accuracy. These approaches convert descriptive microbiome data into actionable decision-support tools, microbiome-based models predicted susceptibility weeks in advance, even at low pathogen abundance (Vega *et al.*, 2022).
- 7. Portable Diagnostics and the Future of Field-Based Detection:** Portable, field-deployable tools represent a frontier in rhizosphere diagnostics, translating complex microbiome data into practical applications. Technologies such as loop-mediated isothermal amplification (LAMP), biosensors, and handheld sequencing enable rapid soil health assessment (Mumford *et al.*, 2016). These approaches can facilitate on-site detection of microbial indicators without specialized laboratories. Combined with simplified microbiome markers, portable diagnostics have the potential to democratize early disease detection.

Translating Rhizosphere Science into Disease Management Strategies

The practical implications of rhizosphere research are profound. If disease risk can be detected early through microbiome indicators, management can shift from crisis response to preventive soil stewardship.

Diagnosis to Prevention: Instead of reacting to visible symptoms, microbiome-informed strategies prioritize prevention, resilience, and ecological balance (Weller *et al.*, 2002). This reflects a shift from pathogen eradication to system-level health management, where disease suppression arises from stable microbial communities. In ginger, such approaches are especially critical, as soil-borne pathogens like *Ralstonia solanacearum* can persist for years without a host, rendering reactive control largely ineffective (Sun *et al.*, 2025).

Soil Health: Healthy soils form the first line of defense against disease. Practices that enhance organic matter, improve soil structure, and minimize chemical stress foster diverse, resilient microbial communities that naturally suppress pathogens (Weller *et al.*, 2002). Implementing crop rotation, organic amendments, and lower chemical inputs can restore microbial balance and rebuild disease-suppressive soil functions (Sun *et al.*, 2025).

Microbiome-guided rotations allow growers to select crops that disrupt pathogen-supportive microbial networks and rebuild beneficial communities (Sun *et al.*, 2025).

Biological control works best ecologically. Beneficial microbes are most effective when introduced into receptive soils, often as consortia rather than single strains, reflecting the collective nature of disease suppression (Berendsen *et al.*, 2012).

Early-warning systems based on simplified microbiome indicators could help farmers time interventions, reduce unnecessary chemical use, and prevent catastrophic losses especially critical for long-duration crops like ginger (Vega *et al.*, 2022).

“The future of diagnosis lies not in detecting pathogens, but in reading ecological warning signs.”

Challenges on the Ground

Despite its promise, microbiome-based management faces practical challenges. Soil variability, climate differences, and limited access to advanced diagnostics complicate large-scale adoption (Quince *et al.*, 2017). Bridging this gap will require simplifying complex data into actionable guidelines, validating approaches under real field conditions, and strengthening extension services (Sun *et al.*, 2025).

Conclusion: Listening to Soil’s Hidden Signals

The rhizosphere is no longer a black box beneath the ginger plant. It is a living archive of biological signals that reveal the earliest stages of disease development. Microbiome science shows that soil-borne diseases are not sudden events, but slow ecological transitions detectable long before crops fail. By learning to decode these hidden signals, ginger cultivation can move beyond pathogen chasing toward ecological and resilient rhizosphere that suppresses disease, reduces chemical dependence and sustains productivity.

“The future of disease management may depend less on fighting microbes and more on working with them.”

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PARADOXICAL ECOLOGY OF SUSTENANCE - ECOLOGICAL ABUNDANCE AND NUTRITIONAL DEPRIVATION: FOOD AND AGRICULTURAL ENVIRONMENT AMONG THE SANTHAL TRIBES OF JHARKHAND

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Introduction

India's indigenous communities (Adivasi) continue to suffer disproportionate malnutrition despite living in resource-rich regions (Singh *et al.*, 2023). The Santhal (Santali) tribe, one of the largest Adivasi groups, is centered in Jharkhand's Santhal Parganas (and adjacent areas of West Bengal, Bihar, and Odisha), with a population exceeding six million (Stiller *et al.*, 2020). Nearly all Santhals are rural smallholder farmers and forest foragers. Tribal groups face deep poverty (about 40% live below the poverty line) and lag on health outcomes; for example, roughly three-quarters of tribal children under five are undernourished and half are stunted nationally (Adhikari *et al.*, 2021). Educational attainment is low, particularly among women, nearly half of whom have never attended school (Ghosh-Jerath *et al.*, 2016). This marginalization is rooted in historical land loss and disenfranchisement, reflected in a declining population share in Jharkhand. This social injustice is a fundamental cause of the community's contemporary nutrition crisis. In Jharkhand, Santhals exhibit particularly high burdens: local studies report nearly 50 percent of women underweight and over 80 per cent anaemic (Ghosh-Jerath *et al.*, 2016; Singh *et al.*, 2023).

The Santhal tribes inhabit an agro-ecological zone rich in forests, water bodies, and traditional farms that support over 500 indigenous foods-54 percent iron-rich and 35 percent calcium-rich (Kapoor *et al.*, 2022; Singh *et al.*, 2023; Ghosh-Jerath *et al.*, 2016). Despite this abundance, severe malnutrition persists, with nearly 50 percent of women underweight and anemia reaching up to 86 percent in some areas. With this background this article, therefore, explores the paradox of ecological richness amid nutritional deprivation, identifying barriers that prevent local biodiversity from enhancing diets and proposing policy pathways to harness indigenous food systems for improving tribal nutrition and health outcomes.

Santhal Food and Agricultural Environment

Traditional Agriculture and Home Gardens

Santhal households typically cultivate small rainfed plots of staple grains. Coarse varieties of rice, maize, and minor millets (e.g. finger millet) are sown on the plateau's red soils with minimal inputs. Pulses (pigeon pea, lentils) and oilseeds supplement these staples. Importantly, nearly every Santhal homestead maintains a *baari* (kitchen garden) of vegetables and greens. One survey in Godda district found almost 100 percent of households had such a garden (Ghosh-Jerath *et al.*, 2016). These *baari* gardens supply leafy greens (amaranths, gourds, pumpkins, etc.) and other micronutrient-rich vegetables that complement the cereal crop.

The nutritional impact of *baari* is significant. Women in households with kitchen gardens exhibit higher vitamin A status (measured by serum retinol-binding protein) and lower inflammation (Singh *et al.*, 2023; Ghosh-Jerath *et al.*, 2016). In other words, even very small plots, if fully utilized, can substantially boost intake of vitamin A, iron, and other micronutrients. The limiting factor appears to be not landed availability but underutilization of cultivable land for diverse crops (Kapoor *et al.*, 2022). Promoting the cultivation and consumption of these garden-grown vegetables could therefore enhance micronutrient intake across communities.

Forests, Wild Foods, and Aquatic Resources

Santhal villages are interspersed with tropical deciduous forests, hills, and seasonal waterways. These natural ecosystems provide a rich supply of non-timber forest products (NTFPs) and aquatic foods. Women and children gather wild leafy greens (moringa leaves, wild amaranth, fern fronds), fruits, roots, tubers, and mushrooms from the forest. Men and older boys harvest fish, snails, and freshwater mussels from village ponds, streams, and rivers (Ghosh-Jerath *et al.*, 2016). These wild foods supplement home-grown crops and are often high in micronutrients.

Studies link access to these natural foods with better nutrition. For example, proximity to a fish pond correlates with higher serum ferritin (an iron marker) in women, indicating that fish consumption raises iron status (Singh *et al.*, 2023). Similarly, households with forest access report greater dietary diversity (Ghosh-Jerath *et al.*, 2016). A recent indigenous food survey identified over 500 plant and animal foods used by Santhals; among these, 54 percent were rich in iron and 35 percent high in calcium (Kapoor *et al.*, 2022). Many of the nutrient-rich foods were wild leafy vegetables and legumes found in the forest.

A flagship example is the *Mahua* (*Madhuca indica*) tree. Each year during the lean season, about 70–75 percent of households harvest Mahua flowers, which are high in sugar content ranging 66–72 percent by dry weight (Mishra & Poonia, 2021). The flowers are dried, cooked, fermented into traditional alcohol (*Handia*), or used as emergency food, providing calories and income when crops are scarce. Similarly, village ponds support small-scale fisheries (e.g. pabda catfish, mollusks) that contribute animal protein and micronutrients. These food sources act as seasonal safety nets and diversify the diet beyond staple grains.

Dietary Patterns and Nutritional Status

Maternal Nutrition

Despite this ecological bounty, Santhal women suffer chronic malnutrition. Field surveys report about half of Santhal mothers are underweight (BMI < 18.5) and over 80 percent are anaemic (Ghosh-Jerath *et al.*, 2016; Singh *et al.*, 2023). These rates exceed Jharkhand state averages (NFHS-5, 2021). Notably, most women consume close to their calorie needs (often >80%), indicating that diet quality, not quantity, is the primary issue. Typical meals consist of refined rice or maize porridge with few accompaniments. Many women obtain less than two-thirds of the recommended intake for iron, calcium, and B vitamins (Ghosh-Jerath *et al.*, 2016). As a result, iron deficiency anemia is virtually universal.

Typical Santhal diets are very low in dairy, meat, and eggs. Analyses show Santhal dietary patterns are high in whole grains (averaging ~475 g/day) but nearly devoid of animal-source foods (Armes *et al.*, 2024). Thus, Santhal women's diets, while energy-adequate, lack key micronutrients. For example, calcium intake covers less than 30 percent of needs without dairy (Ghosh-Jerath *et al.*, 2016). This hidden hunger (micronutrient deficiency) underlies the high anemia and other nutrient-deficiency disorders seen in Santhal mothers.

Child Nutrition and Infant Feeding

The severe deficits in mothers are mirrored in their children. Surveys of Santhal infants and toddlers report extremely high undernutrition. In one study, 52 percent of Santhal children under two were stunted and 49 percent underweight; 73 percent were anaemic (Adhikari *et al.*, 2021). These levels are among the highest reported nationally. Breastfeeding practices are mixed: initiation and eventual breastfeeding are near-universal, but exclusive breastfeeding for six months occurs in only about one-third of infants (Stiller *et al.*, 2020). Complementary foods are often monotonous (thin cereal or lentil gruels), lacking fruits, vegetables, or animal products. Consequently, only about 47 percent of children 6–23 months receive a minimally acceptable diet (Stiller *et al.*, 2020).

In summary, both adult and child nutrition indicators point to a dire situation of ‘hidden hunger’. Santhal children grow up with early micronutrient gaps – an outcome of mothers’ poor diet and limited weaning diets – resulting in pervasive anemia, stunting, and underweight across generations.

The Ecological Nutrition Paradox

This contrast between abundant resources and persistent malnutrition is the Santhal paradox. Traditional Santhal diets have the inherent potential to be nutrient-rich: 54percent of the catalogued indigenous foods are high in iron and 30percent in protein (Kapoor *et al.*, 2022). Historically, forests and fields supplied a variety of vegetables, fruits, legumes, and occasional game, which together could meet dietary needs. Yet in practice many of these resources remain underutilized.

Cultural and economic factors drive this gap. Younger Santhals increasingly prefer milled white rice, wheat flour, and packaged snacks over traditional grains and greens. Gathering wild foods is often stigmatized or viewed as a poverty indicator, reducing the use of forest staples. Time and labor constraints also deter foraging and the laborious preparation of millets or tubers. Market influences and policies have further shifted diets. Government programs (such as the PDS) historically subsidize rice, wheat, and sugar rather than millets or forest products. Consequently, processed foods and refined staples have become symbols of modernity, while diverse indigenous foods are neglected. For instance, field surveys report Santhal women consume an average of only 5 out of the 10 recommended food groups, with very low intake of fruits, dairy, and pulses (Ghosh-Jerath *et al.*, 2016).

This gap between ecological potential and actual diets underlies the paradox: nutrient-dense foods abound in the environment but are “hidden” from people’s plates. Over half of Santhal women eat very little green leafy vegetables, even when readily available (Ghosh-Jerath *et al.*, 2016). Reversing this trend requires both preserving traditional food knowledge and creating incentives (economic, cultural, and policy) for people to use their local biodiversity.

Conclusion

The Santhal tribes of Jharkhand live amid a richly endowed ecosystem, yet face a paradox of abundance and deprivation. The article highlights that while traditional agriculture, kitchen gardens, and forest foods could together meet their nutritional needs, socioeconomic and policy changes have disconnected people from this bounty. Overcoming this paradox requires holistic strategies: protecting tribal land and forest rights, promoting cultivation and consumption of indigenous foods, and integrating these foods into health and welfare programs. By valuing tribal knowledge and engaging communities as equal partners, policymakers can help Santhals translate ecological wealth into sustainable nutrition and health.

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MICROBIAL CONSORTIA OR SINGLE STRAINS? RETHINKING BIOINOCULANT DESIGN

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Introduction

Microbial inoculants are the formulations of the beneficial microorganisms. Microbial inoculants have great potential toward the sustainability of agriculture and climate smart agriculture. When these are applied to seeds, soil or planting material then they colonize the rhizosphere or phyllo-sphere, they increase the crop productivity and resilience of plant under stress conditions. These bioinoculant can serve as alternative of chemicals, and addressing the global concerns such as increasing food demands, scarcity of chemical fertilizer and losses caused by the chemicals.

Biological control of disease using microbial inoculants are relied on antagonistic bacteria, fungi and other beneficial microbes, which suppress the plant pathogen by different direct and indirect mechanism. The mechanism includes competition for nutrient and niches, antibiotic and lytic enzyme production, siderophore secretion, induction of systemic resistance in the host plant and mycoparasitism. Unlike the chemical pesticides the microbial agents are tend to be more target-specific and generally compatible with the native beneficial microbiota, consequently they preserving soil biodiversity and ecological balance. This article will deal with the comparative effectiveness, advantages and challenges of microbial consortia and single-strain inoculant in bioinoculant design for plant health.



Single strain and consortia formulations

Single strain bioformulations contains one specific microorganism to perform a particular agricultural function. The single strain bioformulations generally perform one or a few functions important to agriculture. On the other hand, the microbial consortia is a combination of several microbes that work in the synergistic manner and provide broader range of functions. The microbial consortia are getting attention in now a day.

Advantages of Single Strain Bioformulations

The single strain typically focusses on the one primary function such as *Rhizobium* fix nitrogen in legume, *Azotobacter* fix nitrogen in non-leguminous crops and Mycorrhizal fungi enhance the

phosphorus uptake. These are host specific and environmental sensitive. Despite of this there are several advantages with the single strain bioformulations such as they have targeted action and predicted performance, they contribute significantly to their stability and consistency. The cultivation and maintenance of the single strain is often more straightforward and leading to production of more uniform product. This consistency ensures that each application delivers the intended microbial benefits reliably, which is important for achieving the desired effects and maintaining product integrity over time. Furthermore, single strain formulation is advantageous in the condition where specific microbial functions are required or when the potential interactions between multiples strains are a concern. This approach helpful in minimizing the risk of unforeseen competition or antagonistic effects in multi strain products.

Advantages of Microbial Consortia

The major advantage of the microbial consortia is the broad spectrum of agricultural activities. Consortia have ability to address soil fertility and plant health simultaneously, for example combination of nitrogen fixing bacteria (*Rhizobium*, *Azospirillum*) with phosphorus solubilizing bacteria (Phosphobacteria) and growth promoting fungi (Mycorrhiza). The combined action of multiples strains generally results in synergistic effects, where combined benefit is greater than the sum of individual strain. For examples when we apply *Azospirillum*, *Pseudomonas* and *Methylobacterium* in combination then these consortia enhance plant growth promoting characteristics and disease control more efficiently than the single application. The consortia have better chance to survive in the environmentally diverse conditions because of mutual stimulation and differentiation among the strains. So, they can also help plants to withstand the environmental stresses such as drought and salinity.

Microbial consortia have superior capacity in the bioremediation tasks, such as degrading oil contaminants and polycyclic aromatic hydrocarbons in compare to the single strain. Thus, they can also be used for pollution control. The reports shown that inoculation of consortium increases the plant growth by 48% and pollution remediation by 80% in compare to 29% and 48% respectively for the single strain inoculations (Liu *et al.*, 2023). Moreover, the microbial consortia have shown superior performance under the challenging environmental conditions. For example, in the open field drip fertigated tomato production system where pH is high, fertility is low and sandy soil. They can improve phosphate acquisition and stimulate the vegetative shoot biomass production and increase final fruit yield under the limited phosphorus supply (Bradacova *et al.*, 2019).

Challenges in Bioinoculant Design and Application

Despite the promising aspects of both single strains and microbial consortia, several challenges are also in their development and widespread application.

Challenges for Single-Strain Inoculants

Single species are limited in the functions, perform one or fewer functions. They are also limited to the ecological niches they can occupy; this potentially leads to significantly lower survival rates and reduced functioning because of intense competition with native soil microbial communities. The efficacy of the single strain inoculants generally shows inconsistent in the variable environmental and application methods. Single strain may not be universally adopted and successful across diverse environmental conditions and types of crops, this limits their large-scale applicability. Generally, it has been seen that many bioinoculants perform well under controlled laboratory conditions but fail to achieve the same results in the field. The major cause for bad performance in the field are abiotic

stresses like soil pH, temperature, chemical residues and interactions with native microbes (Ganesh *et al.*, 2023). The maintenance and stability of the the strain over longer period of time is also concern.

Challenges for Microbial Consortia

Microbial consortia offer many advantages but their application is not without difficulties. Microbial inoculation acts as a deliberate disturbance to the native soil microbiome, which can lead to complex interactions between inoculated and native species, resulting in unpredictable and unreliable outcomes. The effectiveness of the consortia depends upon various factors such as diversity and density, application strategies and type of plants. Most microbial inoculants are developed based on laboratory screening and combination, but ensuring their stable survival and function in natural environments remains a significant challenge. In the field condition there is presence of complex environmental disturbances that can weaken the inoculum effects which generally observed in the controlled conditions (Liu *et al.*, 2023). Generally, the greenhouse observation are not fully predicting the performance in the field conditions, so there is much need of robust investigation requires (Liu *et al.*, 2023). Moreover, stability, regulatory concerns and scalability of microbial consortia are also the major challenges for microbial consortia (Kumar *et al.*, 2025). There is also availability of limited studies on the effect of long-term nutrient cycling of biofertilizer and soil biodiversity.

Conclusion and future prospect

Microbial consortia and single-strain inoculants both have significant potential for enhancing plant health and agricultural sustainability. The microbial consortia generally is generally performed better than single strain in plant growth promotion and bioremediation due to its synergistic interaction and broader function's ability. However, development of formulations and application of both formulations face difficulties related to environmental variability, stability and interaction with complex soil microbes. The future research should focus on investigation of microbial consortia in the living soil, and exploring factors which determine inoculation effects and making a robust framework for development of validating consortia before large-scale application. It is crucial to consider soil physicochemical properties, such as pH and nutrient content, as these can significantly influence inoculation success.

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REGENERATIVE HORTICULTURE: MOVING BEYOND SUSTAINABLE GARDENING PRACTICES

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Abstract

Regenerative horticulture represents an evolving approach to plant cultivation that goes beyond conventional sustainable gardening practices by focusing on ecological restoration and long-term system health. Rather than simply conserving resources or reducing environmental harm, it emphasizes working in harmony with natural processes to rebuild soil fertility, enhance biodiversity, and strengthen ecosystem functions. By treating gardens and production spaces as living systems, regenerative horticulture encourages practices that nurture soil life, improve water infiltration, and promote resilient plant communities. This approach responds to growing concerns about soil degradation, climate change, and the ecological limitations of intensive horticultural systems, especially in urban and peri-urban landscapes.

At its core, regenerative horticulture shifts the role of the gardener from a manager of inputs to a steward of ecosystems. Practices such as composting, mulching, intercropping, and minimal soil disturbance help restore biological activity and natural nutrient cycles, leading to healthier plants and more stable yields over time. By integrating native species, encouraging beneficial insects, and increasing plant diversity, regenerative horticulture creates productive spaces that also provide ecological services such as carbon sequestration, improved microclimates, and enhanced resilience to environmental stress. As interest grows in climate-smart and nature-based solutions, regenerative horticulture offers a hopeful framework for transforming gardens into agents of ecological renewal and sustainable food production.

Understanding regenerative horticulture

Regenerative horticulture is an approach to plant cultivation that focuses on restoring and enhancing ecological processes rather than merely maintaining them. It views gardens, farms, and landscapes as living systems where soil, plants, microorganisms, water, and humans are interconnected. Unlike conventional practices that rely heavily on external inputs, regenerative horticulture emphasizes working with natural processes to improve system health over time. The goal is not only to produce food or ornamental plants, but also to rebuild ecosystem functions such as nutrient cycling, soil carbon storage, and biological diversity. It is founded on a holistic set of principles aimed at restoring soil health, enhancing ecosystem functions, and ensuring long-term agricultural sustainability. Central to this approach is the improvement and protection of soil health through practices such as minimal tillage, organic amendments, and continuous soil cover, which help increase soil organic matter, improve structure, and support diverse microbial communities. Biodiversity is actively promoted by integrating crop rotations, cover crops, agroforestry, and mixed farming systems, thereby strengthening ecological balance and reducing pest and disease pressure.

Regenerative horticulture also emphasizes efficient water management by improving soil infiltration and moisture retention, which enhances resilience to droughts and extreme weather events. The responsible integration of livestock through managed grazing supports nutrient cycling, stimulates plant growth, and contributes to carbon sequestration. Additionally, the reduced reliance on synthetic fertilizers and pesticides encourages natural nutrient cycling and biological pest control. Collectively, these principles enable regenerative agriculture to rebuild degraded landscapes, increase productivity over time, and contribute to climate change mitigation by capturing atmospheric carbon and enhancing ecosystem resilience.

Why sustainability alone is not enough

Sustainable horticulture plays an important role in addressing major environmental concerns. Agricultural activities, including horticulture, account for a substantial share of global freshwater consumption and contribute significantly to greenhouse gas emissions. The adoption of resource-efficient practices such as drip and micro-irrigation, agroforestry systems, and organic cultivation methods can greatly lower environmental pressure while supporting climate change mitigation efforts.

Biodiversity conservation is a fundamental component of sustainable horticulture. Pollinators like bees, butterflies, and other insects are vital for the successful reproduction of a large proportion of food crops worldwide. However, their populations are declining due to factors such as habitat destruction and excessive pesticide application. Integrating pollinator-friendly plant species and conserving natural habitats within horticultural landscapes can help restore these essential ecological services.

While sustainable gardening aims to reduce environmental harm and conserve resources, it often falls short in addressing existing ecological degradation. Many landscapes today suffer from depleted soils, loss of biodiversity, and disrupted water cycles—issues that cannot be solved by “doing less harm” alone. Regenerative horticulture goes a step further by actively repairing damaged systems. It shifts the focus from maintaining the status quo to creating net positive outcomes, where horticultural practices contribute to ecosystem recovery, climate resilience, and long-term productivity [kumar, harmani].

Soil health and ecological restoration

Healthy soil forms the backbone of sustainable horticulture by supplying plants with essential nutrients, adequate moisture, and physical support for root development. When soils become degraded through erosion, nutrient loss, or compaction, their ability to sustain productive and resilient cropping systems is severely diminished. The Food and Agriculture Organization reports that nearly one-third of global soils are affected by moderate to severe degradation as a result of unsustainable land-use practices. Beyond crop productivity, soil health plays a critical role in climate regulation through carbon storage. Soils contain significantly higher carbon reserves than the atmosphere, highlighting the importance of soil conservation in mitigating climate change and promoting sustainable agricultural systems.

Techniques to improve and maintain soil health

Several management practices are effective in restoring and maintaining soil quality. Composting is a common approach that converts organic residues into stable, nutrient-rich organic matter. The incorporation of compost enhances soil structure, increases water-holding capacity, and stimulates beneficial microbial activity, while reducing reliance on chemical fertilizers. Studies indicate that

regular compost application can substantially improve soil organic carbon levels over time, leading to greater soil fertility and productivity.

Cover cropping is another valuable practice, involving the cultivation of crops such as legumes and grasses during fallow periods. These plants protect the soil surface from erosion, improve nutrient cycling through nitrogen fixation, and help control weed growth. Evidence from agricultural research shows that cover crops significantly reduce soil erosion and improve water infiltration. Additionally, no-till farming supports soil health by minimizing physical disturbance, thereby preserving soil structure, enhancing moisture retention, and encouraging the buildup of organic matter and soil biodiversity.

Biodiversity, climate resilience, and ecosystem services

In regenerative agriculture, biodiversity, climate resilience, and ecosystem services play interconnected and essential roles in rebuilding healthy agro-ecosystems and ensuring long-term sustainability. Biodiversity forms the ecological backbone of regenerative systems by enhancing both above- and below-ground life. Diverse crops, cover plants, beneficial insects, soil microorganisms, and integrated livestock create balanced food webs that naturally regulate pests and diseases, improve pollination, and enhance nutrient cycling. Increased biological diversity also improves soil structure and fertility through varied root systems and microbial activity, leading to more stable and productive farming systems.

Climate resilience is another key outcome of regenerative agriculture. By increasing soil organic matter and maintaining continuous ground cover, regenerative practices improve water infiltration and moisture retention, allowing farms to better withstand droughts, floods, and temperature extremes. Perennial vegetation, agroforestry, and reduced soil disturbance help sequester atmospheric carbon and lower greenhouse gas emissions, making agricultural landscapes both adaptive to and mitigating factors of climate change. These systems are more resilient to climate variability, ensuring consistent yields and reduced vulnerability to environmental shocks.

Ecosystem services provided by regenerative agriculture support both environmental health and agricultural productivity. Healthy soils enhance nutrient cycling and carbon storage, while diverse plant communities support pollinators and natural enemies of crop pests. Improved water regulation reduces erosion, prevents nutrient runoff, and protects surrounding ecosystems. Together, these ecosystem services reduce dependency on external inputs, lower production costs, and promote sustainable food systems. By strengthening biodiversity and climate resilience, regenerative agriculture restores ecosystem functions while meeting the growing demand for food in an environmentally responsible manner.

Future potential of regenerative horticultural systems

As concerns about climate change, food security, and environmental degradation intensify, regenerative horticulture offers a promising pathway for sustainable transformation. Its principles can be applied across scales from home gardens and urban rooftops to commercial horticultural systems and public landscapes. By integrating ecological knowledge, traditional practices, and modern innovations, regenerative horticulture has the potential to reshape how plants are grown and landscapes are managed. Ultimately, it positions horticulture not just as a productive activity, but as a powerful tool for ecological regeneration and human well-being.

Conclusion

Regenerative horticulture moves beyond the goal of sustainability by actively restoring ecological health within garden systems. Rather than simply reducing environmental harm, it focuses on rebuilding soil fertility, enhancing biodiversity, and strengthening ecosystem functions through practices such as organic soil management, composting, mulching, water-efficient design, and the use of native and pollinator-friendly plants. These approaches transform gardens into productive, self-supporting ecosystems that improve plant health while reducing reliance on synthetic inputs. In addition, regenerative horticulture contributes to climate resilience and environmental restoration by improving soil water retention, promoting carbon sequestration, and supporting vital ecosystem services such as pollination and natural pest control. Applied across home gardens, urban landscapes, and commercial systems, regenerative horticulture helps create resilient green spaces that support food security, ecological balance, and human well-being, offering a practical pathway toward a more regenerative and sustainable future.

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ARTIFICIAL INTELLIGENCE (AI) IN AGRICULTURE

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Abstract

Artificial Intelligence (AI) is rapidly transforming agriculture by enabling data-driven, precise, and sustainable farming practices. Integrating technologies such as machine learning, computer vision, predictive analytics, and IoT-based smart sensors, AI supports informed decision-making in crop monitoring, resource optimization, and automated farm operations. Evidence indicates substantial gains in productivity, yield prediction accuracy, and environmental sustainability through reduced water, fertilizer, and pesticide use. Despite challenges related to infrastructure, cost, and skill gaps particularly for smallholders ongoing technological advancements and policy support are expected to enhance scalability and accessibility. AI thus represents a pivotal tool for addressing food security, climate resilience, and economic viability in modern agriculture.

Keywords: Artificial Intelligence, Smart Agriculture, Precision Farming, Machine Learning, IoT, Sustainable Agriculture.

Introduction: The Digital Revolution in Farming

Defining AI in Agriculture

Artificial intelligence in agriculture represents the integration of computer systems capable of performing tasks that traditionally require human intelligence and decision-making (Azharuddin *et al.*, 2024). This technological revolution encompasses machine learning algorithms, predictive analytics, image recognition, and automated decision-making systems specifically designed to address agricultural challenges. The agriculture sector, which contributes nearly \$330 billion in annual revenue to the economy, is increasingly adopting AI technologies to enhance productivity and sustainability (Patel and Patil, 2022).

The Need for AI in Modern Agriculture

Traditional farming methods are no longer sufficient to meet the growing global demands driven by population increase, climate change, and food security concerns (Patel and Patil, 2022). Farmers face numerous challenges including unpredictable weather patterns, pest management, soil degradation, and resource optimization. AI technology addresses these challenges by providing data-driven solutions that enable precision farming and intelligent resource management (Awasthi *et al.*, 2020).

Core AI Technologies in Agricultural Applications

Machine Learning and Predictive Analytics

Machine learning algorithms form the backbone of AI applications in agriculture, enabling systems to analyze vast amounts of data from sensors, drones, and satellite imagery (Azharuddin *et al.*,

2024). These algorithms can predict crop yields, identify potential diseases, and optimize irrigation schedules based on historical data and real-time environmental conditions. Predictive analytics helps farmers make informed decisions about planting times, resource allocation, and harvest planning.

Image Recognition and Computer Vision

Advanced imaging technologies, including hyperspectral imaging and 3D laser scanning, enable AI systems to monitor crop health, detect diseases, and assess plant growth stages (Javaid *et al.*, 2022). Drone technology provides high-resolution imaging that assists in field monitoring, crop inspection, and data collection for critical agricultural analysis (Patel and Patil, 2022). These visual recognition systems can identify crop ripeness, determine optimal harvest times, and detect areas requiring specific treatments.

IoT Integration and Smart Sensors

The integration of AI with Internet of Things (IoT) devices creates comprehensive smart farming ecosystems (Kose *et al.*, 2022). Smart sensors collect real-time data on soil moisture, temperature, humidity, and nutrient levels, which AI systems process to provide actionable insights for farmers. This integration enables automated irrigation systems, climate control in greenhouses, and continuous monitoring of crop conditions.

Specific Applications of AI in Agriculture

Precision Farming and Resource Optimization

Precision farming represents one of the most significant applications of AI in agriculture, utilizing technology to optimize inputs like water, fertilizer, and pesticides according to specific crop and field requirements (Kaushal *et al.*, 2024). AI-powered systems analyze soil conditions, weather patterns, and crop characteristics to create customized treatment plans for individual plants. This approach has demonstrated remarkable results, with studies showing up to 30% reduction in water usage and 20% decrease in pesticide application (Padhiary *et al.*, 2025).

Crop Monitoring and Health Assessment

AI-powered health monitoring systems provide farmers with comprehensive information about crop conditions and nutritional requirements. These systems utilize image analysis and sensor data to detect early signs of disease, pest infestations, or nutrient deficiencies. Machine learning algorithms can identify specific plant diseases with high accuracy, enabling timely interventions that prevent crop losses and reduce the need for broad-spectrum treatments.

Automated Farming Operations

Intelligent equipment powered by AI can perform various farming operations with minimal human intervention (Kaushal *et al.*, 2024). These systems include automated planting machines that calculate optimal seed spacing and planting depth, robotic harvesters that can identify ripe crops, and autonomous tractors that can navigate fields using GPS and computer vision. Such automation reduces labour costs and increases operational efficiency while maintaining precision in farming operations.

Benefits and Impact Assessment

Productivity and Yield Enhancement

Research demonstrates significant improvements in agricultural productivity through AI implementation. Studies show a 25% increase in crop yields when using AI-driven precision farming

techniques compared to traditional methods (Padhiary *et al.*, 2025). AI-powered predictive models achieve 92% accuracy in crop yield estimation, enabling better planning and risk management for farmers. These improvements directly contribute to addressing global food security challenges while maximizing land use efficiency.

Environmental Sustainability

AI technologies contribute significantly to environmental conservation in agriculture (Kaushal *et al.*, 2024). By optimizing resource usage, AI systems reduce water consumption, minimize chemical inputs, and decrease environmental pollution. The precision application of fertilizers and pesticides based on AI recommendations helps maintain soil fertility while reducing harmful runoff into water systems. Additionally, AI-powered systems help farmers adopt sustainable practices that balance productivity with environmental stewardship.

Economic Benefits

The economic impact of AI in agriculture extends beyond increased yields to include cost reduction and operational efficiency (Padhiary *et al.*, 2025). Studies indicate an 18% decrease in maintenance costs and 15% reduction in fuel consumption through AI-optimized farm machinery management. These cost savings, combined with increased productivity, improve farmers' profitability and make farming operations more economically viable.

Challenges and Limitations

Technical and Infrastructure Barriers

Despite its potential, AI adoption in agriculture faces several significant challenges (Kose *et al.*, 2022). Key obstacles include data availability issues, high operational costs, low digitalization rates in rural areas, and inadequate technological infrastructure. Many farming regions lack reliable internet connectivity and technical support systems necessary for implementing AI solutions effectively.

Skills and Knowledge Gaps

The successful implementation of AI technologies requires technical expertise that many farmers currently lack (Kaushal *et al.*, 2024). There is a significant need for training programs and educational initiatives to help farmers understand and utilize AI tools effectively. Additionally, the complexity of AI systems can be overwhelming for traditional farmers who are accustomed to conventional farming methods.

Cost and Accessibility Issues

High initial investment costs for AI technologies and equipment present barriers for small-scale farmers (Sood *et al.*, 2022). The expense of purchasing drones, sensors, and AI software systems can be prohibitive for farmers with limited financial resources. This creates a digital divide where only large-scale operations can afford to implement comprehensive AI solutions.

Future Prospects and Integration

Emerging Technologies Integration

The future of AI in agriculture lies in the integration of multiple advanced technologies (Kose *et al.*, 2022). The combination of AI with blockchain technology for supply chain transparency, 5G networks for faster data transmission, and advanced robotics for field operations promises to create more comprehensive and efficient farming systems. These integrated solutions will provide farmers with unprecedented control and insight into their operations.

Scalability and Global Adoption

As AI technologies become more affordable and accessible, their adoption is expected to expand globally, particularly in developing regions where agriculture plays a crucial economic role (Kaushal *et al.*, 2024). International cooperation and technology transfer programs will be essential for ensuring that AI benefits reach farmers worldwide, regardless of their economic status or geographic location.

Conclusion

Artificial intelligence represents a transformative force in modern agriculture, offering solutions to critical challenges facing global food production. The evidence demonstrates significant benefits in terms of productivity enhancement, resource optimization, and environmental sustainability. While challenges related to cost, infrastructure, and technical expertise remain, the continued development and democratization of AI technologies promise to revolutionize agricultural practices worldwide. Success in implementing AI in agriculture requires collaborative efforts among researchers, farmers, policymakers, and technology providers to ensure that these powerful tools become accessible and beneficial for all agricultural stakeholders. The future of farming lies in the intelligent integration of technology with traditional agricultural wisdom, creating sustainable and productive food systems capable of feeding the world's growing population.

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BERSEEM (*Trifolium alexandrinum* L.): STATUS, SEED PRODUCTION, AND QUALITY MANAGEMENT

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Abstract

Berseem (*Trifolium alexandrinum* L.), or Egyptian clover, is a pivotal winter legume fodder in South Asia, essential for sustaining mixed crop-livestock farming systems. Despite its high nutritional value and economic significance, seed production in India remains inefficient, creating a large gap between demand and supply that is currently met by imports and the unorganized sector. This article reviews the current status of berseem seed production, analysing the constraints and prospects through a SWOT analysis. It outlines critical agronomic practices-from land preparation to water and weed management, necessary for high-quality seed yield. Furthermore, the paper highlights technological interventions, including the use of plant growth regulators, foliar nutrition, and honeybee-mediated pollination, to enhance productivity. Finally, it discusses seed processing techniques to manage objectionable weeds like chicory, ensuring the availability of quality certified seeds.

Keywords: Berseem, Seed Production, Fodder, Chicory, Pollination

Introduction

Berseem (*Trifolium alexandrinum* L.), widely known as Egyptian clover, is a crucial winter legume fodder crop in South Asia, predominantly grown in the irrigated regions of Punjab. Renowned for its high palatability, multi-cut nature, and rich nutritional profile-containing 20-21% crude protein and 69% total digestible nutrients, it provides sustained forage throughout the seasons. It plays a central role in supporting mixed crop-livestock farming systems, which are fundamental to smallholder livelihoods.

Despite its agronomic importance, seed production remains inefficient and insufficient to meet national demand, leading to a recurring dependence on imported seeds. The current seed yield is approximately 0.2 t/ha, resulting in a Seed Multiplication Ratio (SMR) of 10. While technological innovations could potentially double the average yield to 0.4 t/ha, a significant gap between production and requirement persists. Currently, of the total requirement of 40,000 t of certified seed, only 2,500 t is realized from organized seed production, while 10,000 t is imported, and the remaining 27,000 t is supplied by the unorganized sector. This unorganized sector, where seeds are sold without specific brand names, dominates the market but lacks formal quality assurance.



Fig 1. Seed Production Plot of Berseem

SWOT Analysis of Berseem Seed Production

To understand the production landscape, a SWOT analysis was conducted:

- **Strength:** The gap between demand and supply offers immense scope for high-yielding fodder crops, particularly in peri-urban regions. As a legume, berseem improves soil health by enhancing nitrogen levels and is also identified as a phytoremediation crop.
- **Weakness:** Seed production is weather-dependent and requires pollinators. Additionally, processing seeds infested with chicory requires specialized machines, and the low SMR necessitates large production areas.
- **Opportunities:** India has the largest area under berseem cultivation globally, and the crop is highly demanded across northern, central, and eastern India. Considering the benefit-cost ratio, berseem seed production can be more profitable than wheat or rice.
- **Threats:** The market is dominated by informal systems with uncertain seed quality. Climate change, pesticide misuse affecting bee populations, and a lack of technical knowledge among smallholders pose significant risks.

Seed Quality Maintenance

In India, while certification is optional, labelling is mandatory, and field standards are crucial for preserving quality. Berseem requires specific isolation distances to prevent cross-pollination and maintain genetic integrity.

Table 1: Seed and Field Standards for Berseem 25

Factor	Foundation	Certified
Pure seed (%)	98	98
Inert matter (%)	2	2
Other crop seeds (per kg)	10	20
Total weed seeds (per kg)	10	20
Objectionable weed seeds (per kg)	5	10
Germination including hard seeds (%)	80	80
Moisture (%)	10	10
For vapour-proof containers (%)	7	7

Note: The objectionable weed is *Cichorium intybus* (Chicory/Kasni).

Agronomic Management

- **Land Preparation:** The field must be thoroughly tilled and levelled to create a fine seedbed free of clods, weeds, and pests like termites. This improves soil aeration and water infiltration.
- **Seed and Sowing:** A seed rate of 20-25 kg/ha is recommended, sown between late September and late October. Delays in sowing can reduce fodder yield due to harsh winter conditions. Seeds should be treated with a 1% salt solution to remove floating weed seeds like *Kasni*.
- **Nutrient Management:** Applying 20 kg Nitrogen and 70 kg Phosphorus per hectare before sowing is essential for root development and initial growth.
- **Water Management:** Berseem typically requires 8-10 irrigations, scheduled every 10-15 days depending on soil moisture.
- **Weed Management:** Weed infestation can reduce seed yield by 13-37%. Chicory (*Cichorium intybus*) is a major objectionable weed. Management strategies include using clean seeds, manual removal, and applying Imazethapyr @ 0.1 kg a.i./ha 15-20 days after sowing.

Enhancing Seed Yield

- **Plant Growth Regulators (PGRs):** Foliar sprays timed with flowering can enhance yield. A spray containing Naphthalene Acetic Acid (NAA) at 20 ppm, Gibberellic Acid GA₃ at 50 ppm, and Planofix at 1 ml/L should be applied at the onset of flowering and repeated 10-15 days later.
- **Foliar Nutrition:** Foliar fertilization is highly effective; studies show that salicylic acid (50 mg/L) and KNO₃ (2%) improve seed quality and yield. Foliar application of 2% monoammonium phosphate (MAP) at the flowering stage has also been shown to maximize seed yield.
- **Pollination:** Berseem relies on insect-mediated cross-pollination. Introducing honeybee colonies can improve seed yields by 35% to 67%, significantly increasing seeds per head and 1,000-seed weight.

Seed Processing and Harvesting

Processing involves three main machines: an air screen cleaner, a seed grader, and a specific gravity separator. The specific gravity separator is critical for removing chicory seeds, which have a similar density to berseem; often, seeds must be processed twice or thrice. While advanced machinery like belt drapers and color sorters exist, farmers can also use a saturated salt solution to float and separate chicory seeds.

Harvesting should occur when two-thirds of the pods turn brown. To prevent seed shedding, harvesting is best done in the early morning when dew is present.

Conclusion

Seed production is an underutilized potential of berseem. Addressing the gaps in the seed chain requires a multifaceted approach: promoting organized seed production, utilizing advanced processing technology, and integrating apiculture. Providing proper knowledge and suitable varieties to farmers can transform this crop into a highly profitable enterprise, reducing import dependency and ensuring fodder security.

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ORGANIC MATTER POOLS IN SOIL: COMPOSITION, DYNAMICS, AND FUNCTIONAL SIGNIFICANCE

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Abstract

Soil organic matter (SOM) plays a critical role in regulating soil fertility, nutrient cycling, and ecosystem stability. The distribution of SOM into active, intermediate, and passive pools determines its turnover, stability, and functional contribution to soil processes. Labile pools support microbial activity and rapid nutrient release, while intermediate and passive pools enhance soil structure, nutrient buffering, and long-term carbon sequestration. Understanding SOM fractions and pools provides valuable insights into soil quality assessment and the development of sustainable land management practices under changing environmental conditions.

Keywords: Soil organic matter, SOM pools, Labile carbon, Passive carbon, Carbon sequestration, Soil fertility, Soil health

Introduction

Soil organic matter (SOM) constitutes a central component of soil systems, functioning as a primary reservoir of carbon and nutrients while regulating key soil processes such as nutrient cycling, aggregation, water retention, and microbial activity. The distribution of organic matter into distinct pools determines its stability, turnover rate, and contribution to soil fertility and ecosystem resilience. Understanding SOM pools is therefore critical for sustaining agricultural productivity, enhancing soil health, and mitigating climate change through carbon sequestration. The study of SOM pools provides a mechanistic framework for assessing soil quality and evaluating the long-term impacts of land management practices on soil carbon dynamics.

Definition and Conceptualization of Soil Organic Matter

The concept of soil organic matter has evolved from a static entity to a dynamic and functionally diverse system. Rather than representing a single molecular phase, SOM is now viewed as a continuum of organic compounds varying in origin, chemical composition, and degree of microbial transformation. According to recent interpretations, SOM comprises fresh and partially decomposed plant residues, microbially processed compounds stabilized within soil aggregates, and highly transformed microbial by-products strongly associated with reactive soil minerals. This dynamic nature underlines the importance of SOM pools in regulating soil biogeochemical processes and environmental functions.

SOM Fractions and Pools

The terms *fractions* and *pools* are often used interchangeably, though they represent distinct conceptual approaches. Fractions refer to physically or chemically measurable components of SOM,

while pools denote kinetically defined components differentiated by turnover rates. Separation of SOM into pools enables the assessment of organic matter quality, stability, and functional roles in soil systems. Based on decomposition rates, SOM pools are broadly classified into active (labile), intermediate (slow), and passive (stable) pools.

Active (Labile) Soil Organic Matter Pool

The active SOM pool consists of recently added organic materials that are rapidly decomposed by soil microorganisms. This pool includes fresh plant residues, root exudates, microbial biomass, dissolved organic matter (DOM), and light fraction carbon. Characterized by a short half-life ranging from days to a few years, labile SOM serves as a readily available source of energy and nutrients for soil biota. Due to its rapid turnover, this pool is highly sensitive to changes in soil management and is widely used as an indicator of soil quality.

Labile SOM is dominated by non-humic substances such as amino compounds, phospholipids, and mineralizable carbon and nitrogen, typically constituting 10–20% of total SOM. Microbial biomass carbon (MBC) and dissolved organic carbon (DOC) are particularly responsive to organic amendments and fertilization regimes. Management practices that incorporate high-quality residues with low carbon-to-nitrogen (C:N) ratios, such as legume cover crops, enhance nutrient release from the active pool. However, maintaining long-term SOM stability requires balancing labile inputs with chemically complex residues that decompose more slowly.

Intermediate (Slow) Soil Organic Matter Pool

The intermediate or slow SOM pool represents a transitional phase between labile and stable organic matter. It consists of partially decomposed plant residues, microbial biomass, soluble organic compounds, and humic materials with moderate resistance to decomposition. The half-life of this pool ranges from several years to decades, depending on environmental conditions and residue quality.

This pool includes plant tissues rich in lignin and other chemically resistant compounds, as well as organic matter physically protected within soil aggregates. The slow SOM pool plays a crucial role in improving soil physical properties, nutrient buffering capacity, and sustained nutrient release, particularly nitrogen and phosphorus. Unlike the passive pool, it remains responsive to long-term management practices and contributes significantly to soil structure and fertility.

Passive (Stable or Recalcitrant) Soil Organic Matter Pool

The passive SOM pool comprises highly stable organic materials with turnover times spanning decades to centuries or even millennia. This pool includes humus, charcoal, lignin-derived compounds, and organic matter strongly associated with fine silt and clay particles. Stability arises from biochemical recalcitrance and strong mineral associations, particularly within clay–humus complexes.

Accounting for approximately 60–90% of total SOM, the passive pool is primarily responsible for soil cation exchange capacity (CEC), long-term carbon storage, and water-holding capacity. Although this pool is relatively insensitive to short-term management changes, practices such as residue burning, intensive tillage, and long-term fertilization can influence its quantity and quality over extended periods. Humic substances within this pool enhance soil buffering capacity, moisture retention, and micronutrient availability while reducing metal toxicity through complexation.

SOM Fractions: POM, MAOM, and DOM

SOM can also be categorized into functional fractions based on physical and chemical properties. Particulate organic matter (POM; 53–250 μm) consists of partially decomposed plant residues with wide C:N ratios and represents a labile fraction sensitive to management practices. POM may exist as free POM or occluded POM within aggregates, with the latter being physically protected from decomposition.

Mineral-associated organic matter (MAOM; <53 μm) represents a more stable fraction formed through microbial transformation and sorption onto mineral surfaces such as clays, iron, and aluminum oxides. MAOM is enriched in microbial-derived compounds with low C:N ratios and exhibits turnover times of decades to centuries. Dissolved organic matter (DOM), though small in quantity, plays a vital role in nutrient cycling by supplying readily available substrates to microorganisms and plant roots.

Factors Affecting SOM Pools

Land management practices strongly influence the distribution and dynamics of SOM pools. Tillage practices, in particular, affect particulate organic matter, with conservation and no-tillage systems promoting greater POM accumulation. Long-term fertilization studies demonstrate that combined organic and inorganic nutrient inputs enhance active, slow, and passive pools of soil organic carbon and nitrogen, with higher manure inputs showing the greatest improvements. These findings underscore the importance of integrated nutrient management for sustaining SOM pools and improving soil health.

Conclusion

The study of soil organic matter pools provides a comprehensive understanding of soil fertility, structural stability, and ecosystem functioning. Each SOM pool contributes uniquely to biological activity, nutrient cycling, and long-term carbon sequestration. Sustainable land management strategies that balance organic inputs, minimize soil disturbance, and enhance microbial activity are essential for maintaining a resilient soil system. Continued research into SOM pool dynamics will further support the development of climate-smart and sustainable agricultural practices.

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BEYOND BIOTERRORISM: WHY AGRICULTURE IS THE NEXT STRATEGIC TARGET**Dibyendu Nayak***, Siya Mahi J Nair and Blessin S

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For decades, biosecurity has focused mainly on human health, including pandemics, toxins, and laboratory threats. However, a quieter and more systemic vulnerability lies at the core of modern civilization: agriculture. This article argues that agriculture is becoming the next strategic target not due to dramatic changes but because of structural imbalance. Plant and animal pathogens take advantage of monoculture, genetic uniformity, and highly connected trade networks to cause significant economic and social disruption with little cost to an attacker. Using systems theory and food-security analysis, this paper explores why agroterrorism goes beyond traditional bioterrorism. It also discusses why protecting against it needs genomic surveillance, strong agro-ecosystems, and coordinated policy action instead of just reactive crisis management.

Keywords: Agroterrorism, Biosecurity, Food system vulnerability, Asymmetric warfare, Global food security, Genomic surveillance, Supply chain resilience, Strategic infrastructure

The Strategic Shift: From Bodies to Systems

Bioterrorism, in its traditional sense, targets people. Its goal is to create visibility, panic, casualties, and to assign blame. Agroterrorism, however, targets something much more critical: the systems that sustain life. Food production is biologically vulnerable, spread across different locations, and politically sensitive. Attacks on agriculture do not make headlines. They happen quietly, showing up as failing harvests, mass livestock culls, collapsing exports, and rising food prices.

This change reflects a deeper shift in warfare. Today, power is less about outright violence and more about disrupting systems. Agriculture, which connects biology, economics, and governance, serves as a uniquely effective point of pressure.

Dimension	Classical Bioterrorism	Agroterrorism
Primary Target	Human populations	Food systems (crops & livestock)
Visibility	Immediate, dramatic	Delayed, low visibility
Attribution	Rapid, often clear	Ambiguous, contested
Casualties	Direct human harm	Indirect societal harm
Economic Impact	Secondary	Primary and systemic
Response Trigger	Emergency health response	Trade bans, mass culling, long recovery
Strategic Objective	Fear and panic	Systemic destabilization

Table 1. Bioterrorism vs. Agroterrorism: Strategic Contrast**Asymmetry as a Weapon**

The strategic appeal of agriculture lies in its extreme imbalance.

1. Minimal input, maximal output: Agricultural pathogens need no industrial infrastructure to thrive, but containing them requires significant national mobilization, including testing, quarantines, compensation, trade negotiations, and ecological recovery.
2. Time as a force multiplier: Incubation periods let pathogens spread without detection. By the time symptoms show up, the damage is already part of the system.
3. Plausible deniability: Crop and livestock diseases are common, sensitive to climate, and always changing. It's nearly impossible to prove intent in real time.

This imbalance between effort and result makes agroterrorism not an anomaly, but a sensible strategic choice in an age of asymmetric conflict.

Factor	Attacker Input	Defender Cost
Biological Material	Naturally occurring pathogens	High-level diagnostics & surveillance
Deployment Scale	Minimal, localized	Nationwide response
Time Horizon	Short-term action	Multi-year recovery
Financial Cost	Low	Massive (compensation, trade loss)
Political Cost	Minimal	High (farmer unrest, price inflation)
Legal Risk	Low attribution probability	High accountability pressure

Table 2. Asymmetric Cost–Impact Dynamics in Agriculture

Agriculture Is Engineered for Efficiency, Not Survival

Monoculture: A Biological Single Point of Failure

Modern agriculture has increased yield by reducing genetic diversity. From a biological standpoint, this is a harmful choice. Uniform crops and breeds create large, uninterrupted populations, which are perfect for quick pathogen spread and adaptation. What boosts productivity also reduces resilience.

Global Trade as an Accidental Delivery System

Food systems are some of the most interconnected networks in the world. Seeds, feeds, animals, and equipment move constantly across borders. Ports, processing centers, and storage facilities serve as high-throughput points. Once a pathogen enters these networks, trade becomes the means of transmission.

Livestock Density and Amplification

Industrial animal production packs thousands of genetically similar hosts into tight spaces. Even harmless infections lead to pre-emptive mass culling, causing immediate economic disruption and lasting social distress.

Agriculture, as it is currently structured, does not absorb shocks; it intensifies them.

System Feature	Optimization Goal	Security Consequence
Monoculture cropping	Maximum yield	Genetic uniformity, epidemic amplification
Centralized seed systems	Cost efficiency	Single-point failure
High-density livestock	Productivity	Rapid transmission dynamics
Just-in-time logistics	Reduced storage cost	No buffer against disruption
Globalized trade	Market access	Pathogen dispersal networks

Table 3. Structural Vulnerabilities of Modern Agriculture

Strategic Consequences Without a Battlefield

The power of agroterrorism lies in its indirect effects.

- i. Food insecurity and inflation destabilize societies faster than military attacks.
- ii. Rural collapse erodes livelihoods, accelerates migration, and fuels political unrest.
- iii. Trade isolation follows outbreaks automatically, cutting nations off from global markets.
- iv. Ecological damage, including loss of soil health, genetic resources, and microbial balance, can last for decades.

These outcomes unfold slowly, often below the awareness of traditional security responses, yet they weaken state capacity from within.

Initial Shock	Secondary Effect	Tertiary Impact
Crop failure	Supply shortage	Food price inflation
Livestock outbreak	Mass culling	Farmer insolvency
Export ban	Foreign exchange loss	Trade isolation
Input disruption	Reduced planting	Multi-season yield decline
Rural distress	Migration	Political instability

Table 4. Cascading Consequences of Agricultural Disruption

The Attribution Trap

Perhaps the greatest strategic advantage of agroterrorism is its ambiguity. Natural outbreaks, climate-driven range expansions, and microbial evolution create ongoing background noise. It is extremely hard to tell intent from coincidence.

Genomic analysis can identify anomalies, unusual mutation patterns, and improbable trait combinations, but science alone cannot prove intent. Without shared databases, quick transparency, and political will, even strong forensic signals do not lead to accountability. This results in a threat that is high-impact, low-risk, and legally hard to address.

Defense Must Be Systemic, Not Reactive

Traditional biosecurity focuses on containment after detection. This approach is not enough.

- 1) **Early Warning as Strategic Intelligence** : We need to view environmental monitoring, syndromic surveillance, and rapid diagnostics as national security assets instead of just agricultural services.
- 2) **Diversity as Deterrence** : Genetic, species, and landscape diversity decrease the chance that a single pathogen can cause a widespread collapse. Resilience is not the same as inefficiency—it serves as insurance.
- 3) **Microbiomes as Invisible Shields** : Healthy soil and animal microbiomes function as biological buffers. Managing them is just as important for defense as any physical barrier.
- 4) **Governing Dual-Use Biotechnology** : The same tools that help build resilience can also be misused. Oversight needs to change to manage risks without stifling innovation. Current frameworks have not struck this balance.

International coordination through organizations like the Food and Agriculture Organization is crucial, but it is not enough without being part of national security planning.

7. Policy Blind Spots and Strategic Risk

Agricultural threats exist in a risky gray area; they are viewed as trade issues, veterinary problems, or natural disasters rather than strategic attacks. Current international agreements focus mainly on humans, which leaves food systems vulnerable and not well understood.

To recognize agroterrorism as a strategic risk, we need to:

- i. Clearly include agriculture in biological threat plans
- ii. Invest in shared genomic and surveillance systems
- iii. Add food-system resilience to defense and security policies

Conclusion

Agriculture is becoming the next main target not because it is unimportant, but because it is essential. In a world where countries rely on weak biological supply chains, the strongest weapon may not be one that directly causes death. Instead, it could be one that slowly disrupts the systems that support life. Shifting from bioterrorism to a deeper understanding of agroterrorism is no longer just an academic task. It is a critical necessity.

EVALUATION OF LOCALLY PREPARED BIO-PESTICIDE FROM INDIGENOUS PLANT SOURCES FOR PEST MANAGEMENT IN SPINACH (*Spinacia oleracea*) AND BRINJAL (*Solanum melongena*)

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Abstract

An experiment was conducted under Baba Farid College of Engineering and Technology, Bathinda to evaluate the effect of bio-pesticide and chemical insecticide sprays on pest management, leaf health, and yield of spinach (*Spinacia oleracea*) and brinjal (*Solanum melongena*). Three treatments—control (T1), bio-pesticide spray (T2), and chemical insecticide (T3)—were tested in a randomized design. Pest count reduction, leaf health score, and yield (kg/plot) were recorded. In spinach, T2 (bio-pesticide) resulted in a 65% reduction in pest population, improved leaf health score to 8, and achieved the highest yield of 3.4 kg/plot, representing a 70% increase over the control. Chemical insecticide (T3) showed higher pest suppression (75%) but caused slight leaf phytotoxicity, with yield marginally lower (3.2 kg/plot). In brinjal, bio-pesticide (T2) reduced pests by 60%, enhanced leaf health to 8, and increased yield to 2.9 kg/plot, whereas chemical insecticide (T3) achieved maximum pest reduction (78%) with minor leaf damage and a yield of 3.0 kg/plot. Controls in both crops recorded the lowest pest reduction (0%), poorest leaf health (5 in spinach, 4 in brinjal), and minimum yields (2.0 kg/plot for spinach, 1.8 kg/plot for brinjal).

Keywords: Bio-pesticide, Neem, Garlic, Chilli, Brinjal, Spinach, IPM, Eco-friendly pest management.

Introduction

India is the second largest producer of vegetables after China, about 75 million tons. The existing area under vegetable cultivation in India is around 4.5 million ha. Majority of Indians are vegetarian with a per capita consumption 135 g per day as against the recommended 300 g per day (Dhandapani *et al.*, 2002). In near future, there is a need of around 5-6 million tons of food to feed our 1.3 billion Indian population expected by the year 2020. Indian vegetable export is very low because of increased domestic requirement and other limitations in crop production. Vegetables are more prone to insect pests and diseases mainly due to their tenderness and softness as compared to other crops and virtual absence of resistance characters because of intensive hybrid cultivation. The insect pests inflict crop losses to the tune of 40 per cent in vegetable production. Synthetic chemicals may be used in plant protection programmes to limit crop damage by pests and pathogens. But because of growing concerns about health and environmental safety, the use of toxic, carcinogenic and/or environmentally damaging chemicals is being discouraged. A survey of monitoring the farm gate samples in different parts of the country recorded pesticide residues above maximum residue limit.

Brinjal or eggplant (*Solanum melongena* L.) is an important solanaceous crop of sub tropics and tropics. India is the second largest brinjal producer in the world (about 84.5 lakh tons) (FAO, 2008). Brinjal occupies about 8.45% of the total area under vegetables in India (Patnaik *et al.*, 2004). Brinjal is attacked by a number of insect pests and nematodes during various stages of crop growth in most of the tropical countries including India. The extent of losses caused by these pests depends on season, variety, soil and other factors (Kole *et al.*, 2002).

Pest infestation poses a major threat to vegetable productivity in India, especially in Punjab. Brinjal and spinach suffer significant yield losses due to pests like shoot and fruit borer (*Leucinodes orbonalis*) and aphids. The overuse of synthetic pesticides leads to pest resistance, environmental pollution, and health hazards. Therefore, bio-pesticides from local plants offer a sustainable, low-cost alternative. This research focuses on evaluating a natural formulation composed of neem, garlic, chilli, guava, and akk leaves fermented with jaggery for their combined pest control potential.

The heavy reliance on broad-spectrum chemical insecticides leads to severe consequences, including:

1. High input costs for farmers.
2. Development of pest resistance.
3. Harmful pesticide residues in food, posing human health risks.
4. Damage to non-target beneficial insects, like pollinators and natural enemies.

Materials and Methods

Raw Materials

Neem leaves (1 kg), Garlic (250 g), Chilli (100 g), Guava leaves (1 kg), Akk leaves (1 kg), Jaggery (500 g), Water (10 L), Fermentation container (20 L capacity).

The botanical spray comprises neem leaves, garlic, chilli, guava leaves, akk leaves, jaggery, and water, fermented in a 20 L container. Each ingredient contributes bioactive compounds that enhance plant defense. Neem leaves (*Azadirachta indica*) contain azadirachtin, a potent compound that disrupts insect growth and feeding. Garlic (*Allium sativum*) and chilli (*Capsicum annuum*) provide sulfur compounds and capsaicinoids, which repel pests. Guava (*Psidium guajava*) and akk leaves are rich in phenolic pigments and tannins that strengthen plant resistance against pathogens. Jaggery acts as a fermentation substrate, promoting microbial activity that further enhances the biocontrol potential. Together, these natural ingredients reduce pest attack while being eco-friendly and safe for crops.

Preparation Procedure

Fresh plant materials, including neem leaves (*Azadirachta indica*), garlic cloves (*Allium sativum*), chilli fruits (*Capsicum annuum*), guava leaves (*Psidium guajava*), and akk leaves, were first washed thoroughly and crushed into a fine paste to release their bioactive compounds. Jaggery (500 g) was dissolved in 10 L of water and added to the crushed plant material as a fermentation substrate. The mixture was transferred to a 20 L capacity fermentation container and allowed to ferment anaerobically for 7–10 days at room temperature in the Horticulture Laboratory of the Department of Agriculture, Baba Farid Group of Colleges, Bathinda. During fermentation, microbial activity aided in breaking down plant tissues and enhancing the extraction of secondary metabolites such as azadirachtin, capsaicinoids, sulfur compounds, and phenolic pigments, which contribute to pest control. After fermentation, the extract was filtered through



Preparation of bioextract

muslin cloth to remove solid residues and diluted in a 1:10 ratio with water before application in field trials. This method ensures a standardized bioactive formulation that is eco-friendly and safe for crops.

Experimental Design

Location: Department of Agriculture Research Farm, Bathinda.

Design: Randomized Block Design (RBD).

Treatments: T1 – Control; T2 – Bio-pesticide spray; T3 – Chemical insecticide.

Crops: Spinach and Brinjal.

Observations: Pest count reduction, leaf health, and yield performance were recorded at regular intervals.

Results and Discussion

Table: Effect of Botanical Spray on Pest Control, Leaf Health, and Yield in Spinach and Brinjal

Crop	Treatment	Pest Count Reduction (%)	Leaf Health Score*	Yield (kg/plot)	Mean \pm SE	CD (p=0.05)	CV (%)
Spinach	T1 – Control	0	5	2.0	2.0 \pm 0.1	0.3	6
	T2 – Bio-pesticide	65	8	3.4	3.4 \pm 0.1	0.3	5
	T3 – Chemical	75	7	3.2	3.2 \pm 0.1	0.3	5
Brinjal	T1 – Control	0	4	1.8	1.8 \pm 0.1	0.2	6
	T2 – Bio-pesticide	60	8	2.9	2.9 \pm 0.1	0.2	4
	T3 – Chemical	78	7	3.0	3.0 \pm 0.1	0.2	4

Discussion

- Pest Control:** Both bio-pesticide and chemical treatments significantly reduced pest populations compared to the untreated control. Chemical insecticides had slightly higher immediate pest suppression, but bio-pesticides also achieved substantial control (60–65%), showing good efficacy.
- Leaf Health:** Bio-pesticide treatments maintained higher leaf vigor, likely due to the plant-protective compounds in neem, garlic, chilli, guava, and akk leaves. Chemical sprays, while effective, caused minor phytotoxic effects on sensitive leaves.
- Yield Performance:** Application of bio-pesticide increased yield by 61–70% over control, demonstrating its positive impact on both crop protection and productivity. Chemical insecticides also improved yield but without the eco-friendly benefits of botanical sprays.
- Overall:** The bio-pesticide spray provided a sustainable alternative to chemical insecticides for spinach and brinjal, combining effective pest management with safer, healthier crops.



Spray applies in spinach and brinjal crop

The comparative evaluation of treatments demonstrated distinct differences in pest management, crop health, and yield performance. The untreated control (T1) consistently showed high pest infestation, poor leaf health, and the lowest yield, highlighting the vulnerability of spinach and brinjal to insect attacks without intervention.

The bio-pesticide spray (T2), prepared from neem, garlic, chilli, guava, and akk leaves, showed significant efficacy in reducing pest populations (60–65%) while maintaining excellent leaf health. This improvement is attributed to the synergistic action of bioactive compounds such as azadirachtin, capsaicinoids, sulfur compounds, and phenolics, which provide both insecticidal and plant-protective effects. The yield in T2 plots increased by 61–70% over the control, demonstrating that eco-friendly botanical formulations can enhance crop productivity without causing phytotoxicity.

Chemical insecticides (T3) achieved slightly higher pest reduction (up to 78%) compared to bio-pesticides; however, minor leaf damage was observed, suggesting potential phytotoxic effects. Although the yield improvement with chemical sprays was marginally higher than bio-pesticides, their repeated use poses environmental and health concerns.

Overall, the study indicates that the bio-pesticide spray (T2) offers a sustainable and effective alternative to chemical insecticides, combining satisfactory pest control, improved leaf health, and substantial yield enhancement. This aligns with current research promoting eco-friendly pest management strategies in horticultural crops.

Conclusion

The study clearly demonstrates that the bio-pesticide spray, formulated from neem, garlic, chilli, guava, and akk leaves, is an effective and eco-friendly alternative to chemical insecticides for managing pests in spinach and brinjal. Treatment with the bio-pesticide significantly reduced pest populations, improved leaf health, and enhanced yield, while maintaining crop safety and minimizing environmental impact. Although chemical insecticides provided slightly higher immediate pest suppression, they caused minor leaf damage and pose long-term ecological and health risks. Overall, the bio-pesticide spray offers a sustainable approach to integrated pest

management, promoting healthy crop growth and productivity while reducing reliance on synthetic chemicals. These findings support the adoption of botanical formulations as a practical and environmentally responsible strategy in horticultural crop protection.

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BLUE CARBON COWBOYS: CAN SEAWEED AND SHELLFISH FARMS FIGHT CLIMATE CHANGE

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Abstract

Seaweed and shellfish farms are examples of blue carbon ecosystems that are showing promise as creative ways to address climate change. By assembling large amounts of carbon dioxide through photosynthesis and storing it in biomass or the deep ocean, seaweed farms function as rapidly expanding underwater forests. In addition to purifying water and boosting coastal biodiversity, shellfish like oysters, mussels, and clams store carbon in their calcium carbonate shells. Seaweed and shellfish farms are examples of blue carbon ecosystems that are developing as creative ways to fight climate change. Seaweed farms function as rapidly expanding underwater forests that store carbon dioxide in biomass in the deep ocean after absorbing large volumes of it finished photosynthesis. Oysters, mussels, and clams are examples of shellfish that filter water and improve coastal biodiversity while storing carbon in their calcium carbonate shells.

Key Words: Blue carbon, Seaweed farming, Climate change mitigation, Carbon sequestration

Introduction

One of the most important issues of the twenty-first century is climate change, which is endangering both human societies and ecosystems due to rising temperatures, sea levels, and extreme weather. The potential of seas as natural allies in climate mitigation is becoming more widely recognized, while efforts to cut emissions on land through forests, renewable energy, and sustainable agriculture continue. Seaweed and shellfish farms, sometimes known as "blue carbon" systems, are one of several ocean-based options that are screening promise as creative and efficient carbon dioxide collection and storage technologies. As an underwater forest, seaweed, a rapidly expanding marine plant, absorbs CO₂ during photosynthesis and transforms it into biomass. When seaweed falls into the deep ocean, it can store carbon for a long time or be used sustainably in the production of food, feed, and biofuel. Similar to this, marine biodiversity is supported and water quality is enhanced by the natural filtering of shellfish like clams, mussels, and oysters, which store carbon in their calcium carbonate shells. Beyond sequestering carbon, these blue carbon systems have other advantages. They rehabilitate marine ecosystems, build sustainable lifestyles, strengthen coastal resilience, and supply important resources for industry and human consumption. Increasing seaweed and shellfish production provides a complex, nature-based resolution that simultaneously addresses social, economic, and environmental aspects as climate concerns develop. A sustainable and climate-resilient future may be possible by investigating the possibilities of these "Blue Carbon Cowboys."

Seaweed Farms: Nature's Underwater Carbon Sinks

One of the fastest-growing creatures on Earth, seaweed—often referred to as the ocean's "super-plant"—is essential for mitigating climate change. Seaweed is an environmentally friendly method of sequestering carbon because it doesn't require land, freshwater, or chemical fertilizers like

terrestrial crops do. By taking carbon dioxide from saltwater through photosynthesis and turning it into biomass, seaweed farms act as underwater forests, indirectly lowering atmospheric CO₂ levels and assisting in the fight against ocean acidification. Many seaweed species can absorb carbon more effectively than many land-based plants since they can grow several meters in a matter of months. A part of the carbon contained in seaweed biomass may be carried to deep ocean levels where it can be kept for extended periods of time, or it may be retained through its usage in food, animal feed, biofuels, fertilizers, and biodegradable items. Seaweed farms offer sustainable livelihoods for coastal populations, enhance water quality by absorbing excess nutrients, and provide home for marine species in addition to capturing carbon. Large-scale projects in nations like China, Norway, and Indonesia demonstrate how seaweed farming is becoming more widely acknowledged as a workable, environmentally friendly strategy to combat climate change. Shellfish farms function as potent natural filters that subtly promote ecosystem health and climate mitigation, while seaweed farms function as underwater forests. By creating calcium carbonate shells, shellfish like oysters, mussels, and clams efficiently store carbon in a stable form for extended periods of time. These organisms improve coastal habitats and help to long-term carbon storage as their shells build up on the seafloor. Shellfish simultaneously filter vast amounts of saltwater, eliminating contaminants, excess phytoplankton, and suspended particles, which enhances water clarity and lessens eutrophication in coastal regions.

Challenges and Limitations of Blue Carbon Farming

Blue carbon farming has a lot of potential, but it's difficult to turn that potential into practical climate solutions. Truthfully measuring the amount of carbon that is really sequestered and the duration of its storage is one of the main obstacles. Marine systems are dynamic, unlike terrestrial forests, and if farms are not properly maintained, carbon may be released back into the atmosphere or sea. Integrating seaweed and shellfish farming into official carbon markets and national climate accounting systems is challenging due to this uncertainty. Risks to the environment must also be carefully considered. If carrying capacity constraints are surpassed, large-scale farming may have an impact on neighbouring ecosystems by changing local water flow, light penetration, and nutrient dynamics. Without appropriate biosecurity measures, disease outbreaks, invading species, and genetic effects on natural populations can occur. These systems are also at risk from climate change, which can harm farms and lower productivity due to rising water temperatures, ocean acidity, and greater storms. Economic and social obstacles make expansion even more difficult. Fisheries, tourism, shipping, and conservation frequently share coastal space, which causes disputes over management and access. High initial investment costs, a lack of technical expertise, and a lack of policy support could be obstacles for small-scale farmers. To confirm that blue carbon farming stays sustainable, inclusive, and successful over time, coordinated efforts comprising scientific research, adaptive management, supporting regulations, and significant community participation are needed to overcome these obstacles.

Future Prospects and Policy Support

Blue carbon farming appears to have a bright future, but governments, researchers, investors, and coastal communities must work together to make it successful. Seaweed and shellfish farms can considerably lower atmospheric CO₂, enhance water quality, and restore marine biodiversity, according to a growing body of scientific research. In addition to offering sustainable sources of food, biofuels, and other goods, scaling up these solutions might significantly contribute to national and international climate targets. To realize this potential, policy support is essential. Blue carbon

farming can be encouraged by governments through tax exemptions, subsidies, and participation in carbon credit programs. To manage agricultural settings, guarantee environmental sustainability, and safeguard regional ecosystems, clear regulatory frameworks are required. Funding for research and investment can be attracted by incorporating blue carbon projects into national climate strategies and coastal management plans. Meticulousness aquaculture methods, selective breeding for hardy shellfish, and automated monitoring systems are examples of technological advancements that can increase farm productivity and lower environmental concerns. Since local support guarantees long-term sustainability and fair distribution of economic gains, public awareness campaigns and community involvement initiatives are equally crucial. Seaweed and shellfish farms could play a major role in climate mitigation measures with robust legislative frameworks, management supported by science, and international collaboration. Societies can use nature-based solutions that are both economically practicable and ecologically restorative by viewing oceans as active partners in the fight against climate change.

Conclusion

The "Blue Carbon Cowboys," seaweed and shellfish farms, show that the ocean may be a potent ally in the fight against climate change. These marine farms offer a natural solution that simultaneously tackles social, economic, and environmental issues by increasing coastal biodiversity, improving water quality, and absorbing and storing carbon. While shellfish naturally filter coastal waters and store carbon in their shells, sustaining marine life and protecting shorelines, seaweed functions as a rapidly expanding underwater forest that efficiently captures carbon and provides sustainable products like food, biofuels, and fertilizers. Despite their promise, blue carbon farms face challenges, including accurate carbon measurement, environmental risks, supervisory hurdles, and climate-related threats. Strong policy support, scientific research, technological innovation, and community involvement are all necessary to overcome these challenges. In addition to the benefits of mitigating climate change, expanding such programs can help restore marine habitats and provide coastal populations with sustainable means of subsistence. Seaweed and shellfish farms offer a feasible, low-impact, and scalable alternative as the globe looks for novel ways to combat global warming. Humanity can leverage the ocean's potential to lower greenhouse gas emissions, safeguard biodiversity, and create resilient coastal communities by funding and promoting these nature-based solutions, transforming our marine ecosystems into effective allies in the struggle against climate change.

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ROOFTOP AND BALCONY GARDENING: TURNING CITIES GREEN**Athira S^{1*}, Choudhari Balaji Keshavrao² and Yogesh V. Wayal³**

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Abstract

Rapid urbanization has led to the expansion of concrete-dominated landscapes, often at the cost of green spaces that are vital for ecological balance and human well-being. As cities grow vertically and horizontally, access to land for traditional gardening becomes increasingly limited. In this context, rooftop and balcony gardening have emerged as practical and innovative solutions to reintroduce greenery into urban environments. By transforming underutilized spaces such as rooftops, terraces, and balconies into productive green areas, urban residents can actively participate in creating healthier, more sustainable cities. Rooftop and balcony gardening involve the cultivation of plants ranging from ornamental species to vegetables, fruits, herbs, and even small trees using containers, raised beds, vertical structures, or lightweight growing systems. These forms of urban gardening are adaptable to different scales and socio-economic settings, making them accessible to apartment dwellers, institutions, and commercial buildings alike. Beyond aesthetics, such gardens contribute significantly to urban food security by enabling households to grow fresh, pesticide-free produce, thereby reducing dependence on external food systems and lowering the carbon footprint associated with food transportation.

From an environmental perspective, rooftop and balcony gardens play a crucial role in mitigating the adverse effects of urbanization by reducing the urban heat island effect through building insulation and lower surface temperatures, improving air quality by filtering pollutants and producing oxygen, and enhancing stormwater management by absorbing rainfall and minimizing runoff. These green installations also create valuable microhabitats for birds, pollinators, and beneficial insects, thereby strengthening urban biodiversity and ecological resilience. Beyond environmental benefits, rooftop and balcony gardening offers significant social and health advantages, as regular interaction with plants helps reduce stress, improve mental well-being, and encourage physical activity in densely populated cities where access to natural spaces is limited. Gardening further promotes environmental awareness, community engagement, and a sense of stewardship toward nature. In the context of climate change, rapid urbanization, and declining green spaces, rooftop and balcony gardens emerge as a sustainable and regenerative approach to urban living, reconnecting people with nature while making cities greener, healthier, and more resilient.

What is a rooftop and balcony garden?

Rooftop and balcony gardening is simply about bringing plants into the spaces we already have in our homes on rooftops and balconies especially in cities where open land is scarce. Instead of leaving

these areas empty, they are used to grow plants in pots, grow bags, raised beds, or vertical structures. From colourful flowering plants to leafy vegetables, herbs, fruits, and even medicinal plants, a wide variety of greenery can thrive in these small spaces. In doing so, plain concrete structures are transformed into lively, refreshing green corners that make urban homes more pleasant and inviting. These gardens do much more than just look good. They help improve the urban environment by cooling down buildings and surrounding areas, which is especially helpful in cities that experience high temperatures. Plants naturally absorb carbon dioxide and dust from the air, releasing fresh oxygen and improving air quality. Rooftop gardens can also absorb rainwater, reducing water runoff and easing pressure on city drainage systems. Even on a small scale, these green spaces attract birds, butterflies, and pollinators, quietly supporting biodiversity within crowded city landscapes. Rooftop and balcony gardening enable households to grow fresh, chemical-free vegetables, fruits, and herbs at home, promoting healthier eating while reducing dependence on market produce and the environmental costs of food transportation and packaging. Beyond food production, gardening offers personal and social benefits by reducing stress, improving mental well-being, and providing a calming escape from fast-paced urban life. These green spaces enhance the visual appeal of homes and foster community bonding in apartment settings, making rooftop and balcony gardening a simple yet powerful way to create healthier, happier, and more liveable cities.

Vertical gardening techniques for efficient space use in urban rooftop and balcony gardens

Vertical gardening has become a popular and practical solution for maximizing space in urban rooftop and balcony gardens, where land is scarce and every square inch counts. Instead of spreading plants across the ground, vertical gardening makes use of walls, railings, fences, and specially designed structures to grow plants upward, allowing city dwellers to create lush green spaces even in compact environments. Vertical gardens are especially effective for growing climbers like ivy, beans, and cucumbers, as well as herbs, leafy greens, and flowering plants that thrive in containers. They not only enhance the visual appeal of buildings but also offer environmental benefits by improving air quality, reducing heat absorption, and supporting biodiversity by attracting birds and pollinators. In addition, vertical gardening can help reduce the stress of urban living by providing a natural, calming space, and it encourages sustainable living by enabling residents to grow their own food, even in apartments. With proper planning and support structures, vertical gardening transforms underused rooftops and balconies into productive, healthy, and aesthetically pleasing green zones, making urban living more sustainable and enjoyable.

Popular vertical gardening techniques

1. **Wall planters and living walls** : These are vertical panels or structures attached to walls where plants are grown in pockets or trays. Living walls not only save space but also improve air quality and add beauty to the building.
2. **Hanging pots and baskets** : Hanging pots are a simple and effective way to use overhead space on balconies. They are ideal for flowering plants, herbs, and trailing vines.
3. **Vertical towers and stacks** : Vertical towers are stackable planters that allow you to grow multiple plants in a single vertical column. They are perfect for small balconies and rooftops.
4. **Trellises and climbers** : Trellises support climbing plants like beans, cucumbers, ivy, and climbers. These plants grow vertically and provide shade, privacy, and greenery.
5. **Rail planters** : These are long planters fixed to balcony railings. They are excellent for growing herbs, small vegetables, and decorative plants without taking up floor space.

Balcony garden for vegetable cultivation

Vegetable cultivation in a balcony garden brings the joy of growing food right to one's doorstep, even in the middle of a busy city. A small balcony, when thoughtfully used with pots, grow bags, or vertical stands, can support vegetables like tomatoes, chillies, leafy greens, herbs, and beans. Tending these plants becomes a daily, calming routine watering them in the morning, watching new leaves emerge, and harvesting fresh produce for home cooked meals. Balcony gardening also gives growers the satisfaction of knowing exactly how their food is grown, often without harmful chemicals. More than just a source of vegetables, a balcony garden creates a personal green retreat that connects people with nature while making urban living healthier and more fulfilling.

Balcony vegetable gardens offer multiple advantages that extend beyond individual households and contribute positively to urban sustainability. By enabling the cultivation of fresh vegetables at home, they enhance food security, especially in cities where access to safe and affordable produce can be uncertain. These gardens also encourage the recycling of organic household waste, as kitchen scraps can be composted and reused as nutrient-rich manure, reducing the volume of waste sent to landfills. From an economic perspective, balcony gardening helps urban residents save money on daily vegetable purchases while minimizing dependence on fluctuating market prices. Additionally, growing food at home significantly reduces transportation related emissions associated with the long-distance movement of vegetables from farms to cities, thereby lowering the overall carbon footprint. On a broader scale, the growing popularity of balcony vegetable gardens inspires urban planners and landscape designers to integrate food-producing green spaces into building designs, promoting more resilient, eco-friendly, and people-centered urban environments.

Advantages of roof gardening

Green roofs are widely recognized as an effective solution for lowering external roof temperatures across different climatic conditions. Their benefits extend well beyond energy efficiency, as the vegetation helps absorb and store carbon dioxide, addressing the serious environmental challenges posed by rising CO₂ levels in densely populated urban areas. In addition, green roofs play a significant role in mitigating the urban heat island effect by reducing surface and ambient temperatures. They also enhance rainwater retention, as the soil and plant layers absorb and slowly release rainfall, reducing runoff and pressure on urban drainage systems. Together, these advantages make green roofs a valuable strategy for improving urban environmental quality and resilience [3].

Beyond these advantages, rooftop gardening offers several additional benefits that enhance urban living. Rooftop gardens improve air quality by filtering dust, pollutants, and airborne particulates, creating a healthier microclimate around buildings. They also support urban biodiversity by providing habitats for birds, butterflies, and beneficial insects in otherwise built-up environments. From a social and psychological perspective, rooftop gardens serve as restorative spaces that reduce stress, improve mental well-being, and encourage community interaction in residential and institutional buildings. Moreover, they help protect roofing materials from direct exposure to sunlight and extreme weather, thereby extending roof lifespan and reducing maintenance costs. Rooftop gardening also promotes environmental awareness and sustainable lifestyles by reconnecting urban residents with nature and food production.

Conclusion

In conclusion, rooftop and balcony gardening emerges as a powerful approach to turning cities green by transforming limited and often unused spaces into productive, life-supporting landscapes. By integrating vegetable cultivation on rooftops and balconies, urban residents can grow fresh,

nutritious food while reducing environmental pressures such as heat buildup, pollution, and food transportation emissions. These gardens not only strengthen food and nutritional security but also enhance biodiversity, improve mental well-being, and promote sustainable waste and water management practices. As cities continue to expand vertically, rooftop and balcony gardens offer a practical, people centered solution that reconnects urban communities with nature and food production, paving the way for greener, healthier, and more resilient urban environments.

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SOIL CARBOHYDRATES: NATURE, DISTRIBUTION, COMPOSITION, AND FUNCTIONAL SIGNIFICANCE

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Abstract

Soil carbohydrates are an important and dynamic component of soil organic matter, significantly influencing soil biological activity, nutrient cycling, and structural stability. Derived mainly from plant residues, root exudates, and microbial synthesis, soil carbohydrates occur as monosaccharides, oligosaccharides, and polysaccharides. Their distribution closely follows organic matter content, with higher concentrations in surface horizons. Polysaccharides such as cellulose, hemicellulose, starch, pectins, and chitin play a vital role in soil aggregation, cation exchange capacity, and humus formation. Understanding soil carbohydrate composition and dynamics is essential for improving soil fertility, sustainable land management, and ecosystem resilience.

Keywords: Soil carbohydrates; Polysaccharides; Soil organic matter; Soil aggregation; Nutrient cycling; Microbial activity; Soil fertility

Introduction

Soil carbohydrates constitute a major and functionally important component of soil organic matter (SOM), playing a central role in soil biological activity, nutrient cycling, and structural stability. They serve as readily available energy sources for soil microorganisms and significantly influence organic matter decomposition, metal binding reactions, cation exchange capacity, and soil aggregate formation. Knowledge of the nature, distribution, and composition of soil carbohydrates is essential for understanding soil fertility, assessing soil quality, and developing sustainable agricultural and ecosystem management strategies. In most soils, carbohydrates account for approximately 5–20% of soil organic matter and about 6–14% of total organic carbon, highlighting their quantitative and functional importance.

Nature of Soil Carbohydrates

Carbohydrates are universal constituents of living organisms and represent a substantial fraction of plant and microbial biomass entering the soil system. Chemically, carbohydrates are polyhydroxy aldehydes or ketones or substances that yield such compounds upon hydrolysis. They are generally represented by the empirical formula $C_n(H_2O)_m$ and are composed of carbon, hydrogen, and oxygen. In living systems, carbohydrates perform both structural and metabolic roles. In soils, they influence biological activity as energy sources for microorganisms and contribute to soil chemical properties

through functional groups such as carboxyl (–COOH) groups present in uronic acids, which enhance cation exchange capacity. In plants, carbohydrates are synthesized through photosynthesis, where solar energy converts carbon dioxide and water into glucose. Glucose serves as a precursor for energy storage compounds such as starch and structural polymers such as cellulose. Upon plant death and residue incorporation into soil, these carbohydrates undergo microbial decomposition and transformation, contributing to soil carbohydrate pools.

Classification of Carbohydrates

Carbohydrates are classified based on the number of monosaccharide units they contain. Monosaccharides are the simplest units, while oligosaccharides consist of 2–8 monosaccharide units, and polysaccharides contain eight or more monomeric units. Monosaccharides are further classified as aldoses or ketoses depending on the presence of an aldehyde or ketone group. In soils, most monosaccharides are aldoses, with fructose being the only commonly occurring ketose. Monosaccharides may exist as pentoses or hexoses, depending on carbon chain length. Pentoses such as arabinose, ribose, and xylose and hexoses such as glucose, galactose, and mannose are widely reported in soils. These sugars commonly exist in ring structures, forming furanose (five-membered) or pyranose (six-membered) configurations. Carbohydrates also exhibit optical isomerism due to asymmetric carbon atoms, giving rise to D- and L- forms, which differ in spatial arrangement but share the same molecular formula.

Major Groups of Soil Carbohydrates

Soil carbohydrates include monosaccharides, oligosaccharides, and polysaccharides. Monosaccharides comprise neutral sugars, acidic sugars (uronic acids), amino sugars, sugar alcohols, deoxy sugars, and methylated sugars. Important soil monosaccharides include glucose, galactose, mannose, arabinose, and xylose, with smaller quantities of fucose and ribose. Acidic sugars such as glucuronic and galacturonic acids and amino sugars such as glucosamine and galactosamine are also significant due to their microbial origin. Oligosaccharides such as maltose and lactose yield two to eight monosaccharide units upon hydrolysis. Polysaccharides are the most abundant carbohydrate group in soils and include both homopolysaccharides, such as cellulose, and heteropolysaccharides, such as hemicellulose and microbial gums.

Polysaccharides in Soil

Polysaccharides constitute a major fraction of soil carbohydrates and originate primarily from plant residues, root exudates, and microbial synthesis. In plants, approximately 75% of dry weight consists of polysaccharides, with cellulose being the most abundant naturally occurring organic compound. After plant residues enter the soil, most polysaccharides are decomposed by microorganisms, and the resulting sugars are reutilized for microbial polysaccharide synthesis. Soil polysaccharides are distributed across all humic fractions, particularly in fulvic acids and humins, and may be covalently linked to or adsorbed onto humic substances. In soil science, the term “polysaccharides” often refers to the fraction extractable by water or mild reagents. The composition of soil polysaccharides varies with land use, vegetation, and microbial community structure. Forest soils often exhibit distinct monosaccharide profiles, reflecting the accumulation of microbial-derived saccharides.

Important Polysaccharides: Cellulose, Hemicellulose, Starch, Pectins, and Chitin

Cellulose is the principal structural component of plant cell walls and accounts for 50–70% of carbohydrate inputs to soil. It consists of long linear chains of glucose units linked by β -1,4-glycosidic bonds and has a high molecular weight. Cellulose is decomposed by a wide range of soil

microorganisms through extracellular enzymes that cleave these linkages. Hemicellulose comprises alkali-soluble heteropolysaccharides dominated by xylans and includes polyuronoids and cellulosans. It is more readily decomposed than cellulose and releases simple sugars and uronic acids upon enzymatic hydrolysis. Starch serves as a reserve carbohydrate in plants and consists of amylose and amylopectin, both of which are rapidly decomposed by microbial amylases.

Pectins are polymers of polygalacturonic acid located mainly in plant cell walls and are decomposed by pectin esterase and polygalacturonidase enzymes. Chitin, composed of N-acetylglucosamine units linked by β -1,4 bonds, is an important soil polysaccharide derived mainly from fungal cell walls and insect remains.

Distribution and Composition of Soil Carbohydrates

Total soil carbohydrate content generally parallels soil organic matter distribution, with highest concentrations in organic-rich surface horizons and lower amounts in subsoil layers. Carbohydrate composition is commonly determined using colorimetry, gas-liquid chromatography, and paper chromatography. Neutral sugars dominate soil carbohydrate pools, with glucose being the most abundant. Hexoses are typically present at levels two to four times higher than pentoses, while uronic acids account for approximately 1–5% of organic matter.

Factors Affecting Soil Carbohydrates

Soil carbohydrate content is influenced by fertilization, organic matter inputs, vegetation type, cropping systems, and decomposition rates. Nitrogen fertilization and organic amendments enhance carbohydrate levels, while legume-based cropping systems and permanent pastures exhibit higher carbohydrate contents than fallow systems.

Significance of Soil Carbohydrates

The functional importance of soil carbohydrates arises largely from their role in soil aggregation, where complex polysaccharides bind inorganic particles into stable aggregates. They also contribute to cation exchange capacity, anion retention, and microbial activity, serving as key building blocks for humus synthesis. Certain sugars influence seed germination, root elongation, and nutrient availability, underscoring their ecological and agronomic significance.

Conclusion

Soil carbohydrates are integral to soil structure, fertility, and biological functioning. Their nature, distribution, and composition reflect interactions among plants, microorganisms, and soil minerals. A comprehensive understanding of soil carbohydrate dynamics is essential for improving soil quality, sustaining agricultural productivity, and enhancing ecosystem resilience under changing environmental conditions.

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ENHANCING MORE RESILIENT AND SUSTAINABLE AGRICULTURAL SYSTEM VIA BIOTECHNOLOGY: A GAME-CHANGER IN SUPPLYING THE WORLD'S INCREASING FOOD DEMAND

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Abstract

Agriculture biotechnology applications have had a significant influence on the agricultural sector by engendering multiple benefits and responses to a range of important concerns. Biotechnology had revolutionized crop improvement especially through genetic engineering thereby occasioning the production of transgenic crops with enhanced features/qualities such as higher yield, resistance to pests and diseases, as well as tolerance to environmental challenges. In this respect, these genetically modified crops have increased farmer production and profitability while decreasing the need for chemical inputs. Also, the advent of genetically modified crops had prompted more sustainable and ecologically friendly agricultural practices.

In conclusion, the use of biotechnology in agriculture has changed how crops are produced by giving us tools and approaches to deal with a range of issues. Biotechnology has the potential to be a game-changer in supplying the world's increasing food demand, ultimately resulting in a more resilient and sustainable agricultural system.

Key words: Biotechnology, Agriculture, GMO, yield

Introduction

Biotechnology” has been defined by the Office of the Technology Assessment (OTA) of the U.S. Congress as “any technique that uses living organisms or substances from those organisms, to make or modify a product to improve plants or animals, or to develop microorganisms for specific uses.” It encompasses both “traditional biotechnology,” which includes well-established technologies used in commercially useful operations such as biological control of pests, conventional breeding of plants, animal vaccine production, and cell and tissue culture techniques, as well as “modern biotechnology,” which includes recently available tools for expediting selection and breeding ranging from the use of recombinant DNA, monoclonal antibodies, molecular markers, and transgenic techniques, to genetically engineered live organisms used to modify a variety of characteristics in host plants and animals such as productivity enhancement, growth cycles, and resistance to a variety of environmental or genetic stresses.

The field of biology known as biotechnology makes use of biological things, processes, or creatures to produce goods or technology that is helpful to human existence. Biotechnology can interact with molecular biology, bionics, bioengineering, genetic engineering, and nanotechnology depending on the tools, techniques and applications used. It may also be referred to as the collection of abilities

required to exploit living systems or modify natural processes in order to produce things like habitats, systems, or goods that promote human advancement.

Traditional biotechnologies have been used for thousands of years, including the utilization of yeast to produce wine and bread. Understanding the fundamentals of heredity has given farmers new methods for breeding crops and animals ever since the late 19th century. They created hybrid crops by choosing certain organisms that had advantageous traits.

Since the 1954 discovery of the DNA structure, new techniques have been created. For instance, it is possible to modify plant genetics to make them resistant to pests or disease, and microorganisms may be employed to create medications.

By creating medications and other remedies for illnesses, boosting food yields, lowering environmental pollution, etc., modern biotechnology continues to have a significant positive influence on prolonging human longevity and improving quality of life. Plants and crops may be modified through biotechnology to survive external stressors like spatial constraints or extreme weather.

In agriculture, biotechnology has become a potent instrument that has transformed how food is produced and increased crop yields. Biotechnology uses in agriculture have revolutionized traditional agricultural practices and have enormous potential for future improvement. Biotechnology has aided in the production of genetically modified crops with better features by leveraging the power of genetic engineering. This has allowed for higher productivity, less pesticide use, and improved resistance to environmental challenges.

Similarly, biotechnology instruments promote precision agriculture and the protection of plant genetic resources, which helps to promote sustainable agricultural practices. As biotechnology advances, it has the potential to play an important role in addressing global food security concerns and encouraging ecologically friendly agricultural practices. The benefits from agricultural biotechnology accrue to the scientists from the precision and reduced costs of research as well as to society from the production, productivity, improved quality of life, improved incomes, reduced consumer prices and related benefits of a wide variety of biotechnology products.

Literature Reviews

Application of biotechnology in agriculture

In agriculture, biotechnology is often used to increase nutritional value, increase resistance to pests and diseases, and improve crop growth and yield. In fact, it is estimated that up to 80% of all prepared meals on the market today contain ingredients derived from biotechnology. There are many examples of biotechnology in agriculture, from genetically modified crops to sterile pest management (SIT) techniques for insect control on fruit trees and vines.

The capacity to control DNA, the chemical component that defines the properties of living organisms, at the molecular level was made possible by developments in molecular biology in the 1970s. Genetic engineering is the name given to this technique. Additionally, it enables DNA exchange between species across a wider range of distances than conventional breeding methods.

Today's technology has advanced to the point that researchers may extract one or more particular genes from practically any creature, including bacteria, viruses, plants, or mammals and insert those genes into an entirely other organism. A transgenic organism or genetically modified organism is one that has undergone genetic engineering. Most common use cases are as follows:

Genetically modified crops

Genetically modified organism (GMO) refers to an animal, plant, or microbe whose DNA has been altered via the use of genetic engineering techniques. The term "genetically modified" is ambiguous and might be misunderstood because nearly everything we consume has undergone genetic alteration as a result of domesticating wild species and a number of generations of human selection for advantageous traits. The genetic make-up and how it interacts with the environment determine the qualities of all living organisms. The genome, which is composed of DNA in all plants and animals, contains the genetic make-up of an organism. Genes, which are sections of DNA that often carry the instructions for constructing proteins, are found throughout the genome. These proteins are the cause of the plant's distinctive traits. For instance, genes that carry the instructions for building proteins required to make the pigments that give petals their colour are responsible for deciding the hue of flowers. Plants can have particular DNA sequences inserted into their genomes to give them new or distinct traits. It could be essential to alter the plant's growth pattern or provide it disease resistance for this. The seeds produced by these plants will integrate the extra DNA into the genome of the GM plant.

Insect resistance

Some crops have recently undergone genetic modification to create their own Bt proteins, making them resistant to particular insect species. A soil bacterium known as *Bacillus thuringiensis*, sometimes known as "Bt," produces a protein that is poisonous to a certain class of insects but not to animals or people. Before the present Bt crops were established utilizing biotechnology, applications of Bt bacteria were used for many years to control insect pests. Commercial production of maize and cotton cultivars with bt insect resistance has already begun. Cowpeas, sunflower, soybeans, tomatoes, tobacco, walnut, sugar cane, and rice are a few of the other crops being studied.

Herbicide tolerance

Farmers often utilize chemical pesticides to manage weed growth, as weeds compete with crops or essential resources like soil nutrients, water, and sunlight, leading to reduced crop yields. In modern agricultural practices, herbicides are directly applied to crops to control weed growth. Farmers employ combinations of different herbicides once plants start to grow since these herbicides usually have selective effects, targeting only specific plants while preserving the crops. To simplify weed control and promote the use of safer chemicals, scientists have explored genetically engineering crops to possess tolerance towards a wide range of herbicides. This genetic modification has been implemented in various crops, including corn, soybeans, cotton, canola, sugar beets, rice and flax, with some of these genetically modified varieties being available in multiple countries.

Virus resistance

Plant viruses, often transmitted through insect vectors like aphids, have the potential to affect a wide range of plant species, leading to significant crop damage. Controlling the spread of viral infections poses considerable challenges. Although insecticides are sometimes used to reduce the population of disease-carrying insects, they generally have limited impact on the transmission of the virus itself. Cultural controls, such as removing infected plants, and the cultivation of virus-resistant or tolerant plant varieties are typically the most effective methods to combat viral infections. However, these approaches may not always be feasible or cost-effective. To address this issue, scientists have developed innovative genetic engineering techniques that offer new possibilities for conferring resistance to viral infections, expanding the options available for control and prevention.

Enhanced nutritional value in foods

To improve their nutritional worth, crops can be genetically modified to include more vitamins. In genetically engineered "golden rice," for example, three genes have been added to allow plants to produce beta-carotene, which the human body converts into vitamin A. The leading cause of blindness in children, vitamin A deficiency, affects up to 250 million of them globally.

Biotechnology has also been used to change the composition of certain oil crops in order to increase the amount of oil they produce or to change the kind of oils they produce.

Increased crop productivity

Biotechnology has contributed to enhanced crop productivity by introducing traits such as improved drought tolerance and disease resistance. Researchers now have the ability to select disease resistance genes from other organisms and incorporate them into important crops. An example of this is the transfer of a virus gene to papaya plants, resulting in the creation of two papaya varieties resistant to papaya ring spot virus. These virus-resistant papaya varieties, known as "SunUp" and "Rainbow," have been distributed to papaya producers since 1998 through licensing agreements. In regions with arid climates where efficient water utilization is crucial, biotechnology offers additional opportunities. By introducing genes from naturally drought resistant plants, many crop types can be made more drought-tolerant.

Conclusion and Recommendation

Conclusion

Biotechnology applications in agriculture have had a significant influence on the sector especially in addressing several concerns.

Recommendation

All stakeholders in agriculture should adopt biotechnology products especially the transgenic crops with enhanced features such as higher yield, resistance to pests and diseases, and tolerance to environmental challenges in order boost farmers' production, income level and profitability thereby fostering sustainable productivity.

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CBD-INFUSED FOODS AS EMERGING FUNCTIONAL FOODS: HEALTH BENEFITS, CHALLENGES AND FUTURE PROSPECTS

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Abstract

Cannabidiol (CBD)-infused foods are emerging as a novel category of functional foods due to their potential health-promoting properties beyond basic nutrition. CBD, a non-psychoactive phytocannabinoid primarily derived from industrial hemp, has been reported to exhibit anti-inflammatory, antioxidant, anxiolytic, neuroprotective and gastrointestinal modulatory effects. This article highlights the functional relevance of CBD-infused foods, focusing on their health benefits, nutritional value, safety concerns, regulatory challenges and future prospects. CBD enriched food products may support mental well-being, pain management and gut health, while hemp-based ingredients contribute high-quality proteins, polyunsaturated fatty acids, vitamins and minerals. Despite these benefits, the incorporation of CBD into food systems faces significant challenges, including regulatory uncertainty, lack of standardized dosage guidelines, variability in bioavailability and limited long-term safety data. Recent advancements in extraction techniques, encapsulation and delivery systems—particularly nanotechnology-based approaches—show promise in improving CBD stability and bioavailability in functional food matrices. With increasing consumer awareness and market growth, CBD-infused foods hold considerable potential; however, harmonized regulations and robust scientific validation are essential to ensure their safe and responsible commercialization.

Keywords: Cannabidiol, CBD-infused foods; Functional foods, Nutraceuticals, Food safety, Regulatory challenges.

Introduction

Cannabidiol (CBD)-infused foods are emerging as a significant category within the functional foods market, offering potential health benefits alongside various challenges and future prospects. These products leverage the bioactive compounds found in cannabis, particularly CBD, to provide therapeutic effects such as pain management, anti-inflammatory properties, and potential benefits for mental health conditions. However, the integration of CBD into food products is not without its challenges, including regulatory hurdles, safety concerns and the need for further research to substantiate health claims. The future of CBD-infused foods will likely depend on advancements in scientific research, regulatory frameworks and consumer acceptance.

Health Benefits of CBD-Infused Foods

Therapeutic Effects: CBD is known for its potential to alleviate symptoms of anxiety, depression and epilepsy and it may also offer benefits for conditions like Tourette Syndrome and sleep disorders (Santos *et al.*, 2024). Additionally, CBD has been associated with anti-inflammatory, antioxidant and anticancer properties, which could make it a valuable component of functional foods (Charles *et al.*, 2024) (Martinez *et al.*, 2020). Ongoing research is essential to fully understand the implications of incorporating CBD into food products and to establish safe consumption guidelines.

Gut Health: Hemp seeds, a common source of CBD, have been shown to enhance gut health by improving intestinal barrier function and reducing inflammation (Cheng *et al.*, 2025). This suggests that CBD-infused foods could play a role in promoting digestive health. Moreover, the therapeutic potential of CBD in gastrointestinal health aligns with findings suggesting it may help manage inflammatory bowel disease and improve overall gut function (Brown *et al.*, 2024). Further investigation into the specific mechanisms by which CBD influences gut health will be crucial for optimizing its application in dietary interventions for inflammatory bowel disease and similar conditions.

Nutritional Value: Hemp seeds are rich in protein, polyunsaturated fatty acids, vitamins, and minerals, contributing to their status as a nutritionally valuable food ingredient (Kamle *et al.*, 2024). Furthermore, the incorporation of CBD into various food products could enhance their appeal by providing additional health benefits, thus catering to the growing consumer demand for functional foods (Charles *et al.*, 2024). However, the lack of comprehensive regulations and established dosage guidelines poses significant challenges for manufacturers and consumers alike.

Challenges in CBD-Infused Foods

Regulatory Issues: The legal status of CBD varies globally, with many regions lacking clear guidelines for its use in food products. This regulatory uncertainty poses a significant barrier to the widespread adoption of CBD-infused foods (Rasera *et al.*, 2021) (Siddiqui *et al.*, 2023). As regulations evolve, stakeholders in the food industry will need to navigate these complexities to ensure compliance and consumer safety.

Safety and Dosage: There is a need for precise dosage guidelines to ensure consumer safety, as the effects of CBD can vary based on individual factors (Fordjour *et al.*, 2024) (Siddiqui *et al.*, 2023). Additionally, the potential side effects of CBD, such as interference with drug metabolism and liver function, must be considered (Santos *et al.*, 2024). The importance of establishing clear regulatory frameworks and safety guidelines cannot be overstated, as they will be essential for the responsible integration of CBD into food products.

Research Gaps: While there is promising evidence for the health benefits of CBD, more scientific research is needed to validate these claims and understand the long-term effects of CBD consumption (Bartončíková *et al.*, 2023) (Charles *et al.*, 2024). Addressing these research gaps will be crucial for establishing the efficacy and safety of CBD-infused foods in the marketplace.

Future Prospects

Innovation in Product Development: The food and beverage industry is exploring innovative ways to incorporate CBD into a variety of products, from beverages to baked goods, which could expand the market for CBD-infused foods (Rasera *et al.*, 2021). As consumer interest grows, companies are likely to increase their investment in research and development to create new CBD-infused products that meet regulatory standards and consumer expectations.

Advancements in Extraction and Delivery: Improved extraction methods and delivery systems, such as nanotechnology, could enhance the bioavailability and efficacy of CBD in food products, making them more appealing to consumers (Santos *et al.*, 2024). As advancements in research and regulatory clarity unfold, the market for CBD-infused foods is poised for significant growth, with potential innovations across various product categories.

Consumer Acceptance and Market Growth: As consumer awareness and acceptance of CBD increase, the market for CBD-infused foods is expected to grow significantly, with projections indicating substantial market expansion in the coming years (Rasera *et al.*, 2021).

Conclusion

The potential of CBD-infused foods as functional foods is promising, it is crucial to address the challenges associated with their use. Regulatory clarity, safety assurance and robust scientific evidence are essential to ensure the responsible development and consumption of these products. As research continues to evolve, CBD-infused foods may become a staple in the functional foods market, offering consumers a novel way to enhance their health and well-being.

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CLIMATE-SMART AGRICULTURAL EXTENSION: PREPARING FARMERS FOR CLIMATE CHANGE ADAPTATION AND MITIGATION

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Abstract

Climate change poses increasing challenges to Indian agriculture through erratic monsoons, rising temperatures, extreme weather events, and heightened production risks, particularly for small and marginal farmers. In this context, conventional agricultural extension approaches focused primarily on technology transfer are no longer sufficient. This article examines the emergence and significance of climate-smart agricultural extension (CSAE) as a transformative approach to strengthening farmer's adaptive capacity under climate variability. It discusses key components of CSAE, including participatory learning, climate literacy, digital and agrometeorological advisory services, and inclusive gender-responsive strategies. The article highlights the growing role of digital technologies in delivering timely, location-specific advisories and presents a case study from Haryana demonstrating how climate services integrated into extension systems improve farm-level decision-making, resource-use efficiency, and economic outcomes. It concludes by identifying challenges and outlining strategic directions for scaling climate-smart extension to enhance resilience, sustainability, and food security in Indian agriculture.

Keywords: Climate-smart Agricultural Extension, Climate change, Climate resilience, Climate services

Introduction

Agriculture in India is increasingly shaped by climate uncertainty. Erratic monsoons, delayed onset of rainfall, prolonged dry spells, rising temperatures, floods, and extreme weather events are becoming more frequent and intense. These changes directly affect crop productivity, livestock health, farm incomes, and national food security. With nearly 55 per cent of India's net sown area being rainfed and dominated by small and marginal farmers, vulnerability to climate variability remains high. Climate change amplifies existing production risks by altering cropping calendars, increasing evapotranspiration, intensifying pest and disease pressure, and reducing the reliability of traditional farming knowledge. As a result, farmers face greater uncertainty in making decisions related to sowing, irrigation, nutrient application, and pest management. In this context, agricultural extension education becomes a critical institutional mechanism for strengthening farmers' adaptive capacity.

Conventional extension systems in India historically emphasized yield enhancement through technology transfer. While this approach contributed significantly to food security, it is no longer sufficient under climate variability. Farmers now require climate-responsive knowledge, real-time information, and risk management skills. This has led to the emergence of climate-smart agricultural

extension (CSAE), which integrates climate science, digital advisory systems, and participatory learning to support informed and adaptive farm level decision-making (Kumar *et al.*, 2022).

What is Climate-Smart Agricultural Extension

Climate-smart agricultural extension refers to extension systems and educational approaches that facilitate the adoption of climate-smart agriculture (CSA) at farm and community levels. CSA is grounded in three interrelated objectives:

1. Sustainably increasing agricultural productivity and incomes,
2. Strengthening adaptation and resilience to climate variability and change, and
3. Reducing or avoiding greenhouse gas emissions where feasible (Lipper *et al.*, 2014).

CSAE differs fundamentally from conventional extension by emphasizing anticipatory and risk-informed decision-making rather than reactive responses after crop losses occur. Extension personnel function not only as technology disseminators but also as facilitators who help farmers interpret climate information, evaluate alternatives, and choose context-specific responses. In India, climate-smart extension increasingly integrates agrometeorological advisories, climate-resilient technologies, and indigenous knowledge systems. This integration allows farmers to align management decisions with evolving climate signals, thereby reducing exposure to production risks (Kumar *et al.*, 2022).

New Approaches in Climate-Smart Extension Education

Climate-smart extension education represents a shift from linear knowledge transfer to participatory, learning-oriented approaches. A central element of this transition is the enhancement of climate literacy among farmers. Climate literacy enables farmers to understand rainfall variability, temperature extremes, and climate induced pest and disease dynamics, and to relate these changes to farm management decisions. Participatory approaches such as farmer field schools, village-level climate risk assessments, and seasonal planning exercises have gained prominence. These methods encourage farmers to analyze their own production systems, experiment with adaptive practices, and share experiences within their communities. Evidence suggests that such participatory learning approaches improve farmers' understanding of climate risks and strengthen trust in extension advisories (Davis *et al.*, 2012). Furthermore, interdisciplinary convergence between extension, meteorology, and natural resource management has enhanced the relevance of climate-smart recommendations. Integrating climate information into advisory services allows extension systems to move beyond generalized recommendations toward locally appropriate, climate responsive guidance.

Digital Tools Powering Climate-Smart Extension

Digital technologies now form the backbone of climate-smart extension systems in India. Advances in weather forecasting, remote sensing, and data analytics have enabled the delivery of timely, location specific advisories that support critical farm decisions (Lipper *et al.*, 2014). Agrometeorological advisory services provide farmers with information on rainfall probability, temperature trends, and extreme weather risks, along with crop-specific management recommendations. Empirical studies show that farmers who receive and use such advisories adjust sowing dates, irrigation schedules, and input use more effectively, thereby reducing climate-related losses (Manjunath *et al.*, 2024). Mobile phones, SMS alerts, and digital platforms also facilitate rapid dissemination of advisories and peer-to-peer learning. These tools reduce information asymmetry, improve responsiveness during critical crop growth stages, and enhance farmers' confidence in climate-based decision-making.

Climate-Smart Practices Promoted Through Extension

Climate-smart agricultural extension promotes a portfolio of adaptive and sustainable practices tailored to diverse agro-ecological contexts. Key practices include:

- ❖ Adoption of climate-resilient crop varieties tolerant to drought, heat, or flooding
- ❖ Efficient water management, including micro-irrigation and weather-based irrigation scheduling
- ❖ Soil health management, conservation agriculture, and residue retention
- ❖ Integrated pest and disease management informed by climate-based forecasts
- ❖ Crop diversification, intercropping, and agroforestry to spread risk

Through demonstrations, participatory trials, and farmer-to-farmer learning, extension systems help farmers evaluate the long-term benefits of these practices. Research indicates that such integrated approaches enhance yield stability and resilience under climate stress (Kumar *et al.*, 2022).

Reaching the Most Vulnerable: Inclusive Extension Strategies

Climate change impacts are socially differentiated. Smallholders, women farmers, and resource-poor households often face higher exposure to climate risks and lower adaptive capacity (Lipper *et al.*, 2014). Climate-smart extension therefore emphasizes inclusive and gender-responsive strategies. Studies highlight the critical role of women in agricultural adaptation, particularly in seed selection, water management, and household food security. However, women often face barriers in accessing extension services (Davis *et al.*, 2012). Gender responsive extension approaches such as targeted training, flexible delivery mechanisms, and participatory learning improve adaptation outcomes and strengthen household resilience. Youth engagement through digital platforms and climate-smart entrepreneurship further enhances the sustainability of extension systems by creating local adaptation leaders (Lipper *et al.*, 2014).

Case Study: Impact of Climate Services on Farm Decision-Making in Haryana, India

- ❖ **Background:** Wheat and rice cultivation in Haryana is highly sensitive to climate variability particularly fluctuations in temperature, rainfall, and extreme weather events during critical crop growth stages. Farmers often face uncertainty in operational decisions such as sowing time, irrigation scheduling, fertilizer application, and harvesting, which directly affects productivity and profitability. In this context, climate services delivered through agricultural extension systems have emerged as an important climate-smart intervention.
- ❖ **Extension Intervention:** A study by Manjunath *et al.* (2024) evaluated the role of climate services including weather forecasts and agro-advisories in supporting farm-level decision-making among wheat and rice farmers in Haryana. These climate services were disseminated through extension mechanisms and provided timely, actionable information related to expected weather conditions and suitable farm operations. The advisories guided farmers on:
 - Optimal timing of sowing and transplanting
 - Irrigation scheduling based on rainfall forecasts
 - Input management decisions to avoid weather-related losses

Such services represent a key component of climate-smart agricultural extension, as they translate climate information into practical guidance for farmers.

- ❖ **Outcomes:** The study reported that farmers who accessed and used climate services made more informed operational decisions compared to non-users. Key outcomes included:

- Improved irrigation efficiency, resulting in reduced water use and lower production costs
- Better timing of farm operations, helping farmers avoid adverse weather events
- Positive economic outcomes, particularly in terms of cost savings and improved profitability in wheat and rice cultivation

These findings demonstrate that climate services, when effectively integrated into extension systems, can significantly enhance farmers' adaptive capacity under climate variability (Manjunath *et al.*, 2024).

This case study clearly illustrates how climate-smart agricultural extension operationalizes climate information to support farmer decision-making. By enabling farmers to anticipate weather risks rather than respond after losses occur, climate services strengthen resilience, improve resource-use efficiency, and contribute to sustainable agricultural development. The Haryana experience highlights the importance of scaling up climate services within extension systems as a core strategy for climate adaptation in Indian agriculture.

Challenges Faced

Despite significant progress, several challenges constrain the effectiveness of climate-smart extension. Limited access to digital infrastructure restricts advisory reach among resource-poor farmers. Capacity gaps among extension personnel in climate interpretation and communication persist. In addition, the availability of high-resolution, location-specific climate data remains uneven, affecting advisory accuracy (Kumar *et al.*, 2022).

The Way Forward

Strengthening climate-smart agricultural extension requires sustained investments in human capacity, digital infrastructure, and institutional coordination. Priority areas include:

- Integrating climate risk management into extension curricula
- Continuous training of extension professionals
- Strengthening linkages between climate services and extension systems
- Scaling participatory and farmer-led advisory models

Such efforts are essential to maintain agricultural productivity and resilience under increasing climate uncertainty.

Conclusion

Climate-smart agricultural extension represents a vital pathway for enhancing farmers' resilience to climate change in India. By linking climate science with farm-level decision-making, extension services enable farmers to anticipate risks, adopt adaptive practices, and stabilize livelihoods. As climate variability intensifies, CSAE will remain central to sustainable agricultural development and food security.

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COLD PLASMA PROCESSING: AN EMERGING NON-THERMAL TECHNOLOGY FOR FOOD SAFETY AND QUALITY PRESERVATION

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Abstract

Cold plasma technology is finding applications as an innovative non-thermal processing technology that can effectively improve microbial safety without compromising the quality and nutritional integrity of foods. It is commonly linked with the visible purple or blue glow of the technology, or "purple lightning," that personifies the cold plasma technology as a representation of its intense but low-temperature processing mechanism. Cold plasma is characterized by a complex pattern of oxygen and nitrogen species, ions, ultraviolet radiation, and electric fields that collectively work for microbial inactivation. This review focuses on an in-depth analysis of the principles of cold plasma technology in the context of their application in food processing tasks, including the principles of microbial inactivation by these systems for fruits, vegetables, meats, poultry products, fish products, cereal products, nuts, seeds, and spices. Additionally, it explores critical discussions related to the role of cold plasma systems on the nutritional integrity of foods, their applications for innovative food packaging systems, current gaps with respect to industrial development, standardization, and recognition of the systems for global applications, and, finally, important areas of research for ensuring effective applications of cold plasma technology for safe food preservation practices.

Keywords: Cold plasma technology; Purple lightning preservation; non-thermal food processing; Microbial inactivation; Food safety; Food quality; Active food packaging; Shelf-life extension

Introduction

A major challenge in the food industry is the need to keep food free from harmful microbes while maintaining its sensory and nutritional value. Most of the current methods for keeping food safe from microorganisms (such as heat treatment, chemical sanitation, and radiation) reduce the number of microorganisms but also alter the food's taste, smell, colour, texture, and nutrition. In addition, consumers increasingly desire minimally processed, fresh-tasting, and preservative-free foods, which has prompted the development of alternative, non-thermal methods for food preservation.

Cold plasma has recently attracted much attention as a potential solution to these problems. Unlike heat-based processes, cold plasma works at room temperature (or slightly below). Cold plasma consists of a mixture of gases with some of the gas molecules having lost some of their electrons. This can create an environment that can destroy microorganisms on food. The characteristic purple light generated when plasma is produced is referred to as "purple lightning" to describe its energetic, but not heat producing, nature.

The area of cold plasma research has grown rapidly over the past ten years as scientists have found that cold plasma can effectively kill many different types of foodborne pathogens and spoilage organisms. Cold plasma technology is now being extensively researched and used on a variety of

different food types, including fruits and vegetables, meats and dairy products, dry goods, and food packaging material. Despite promising laboratory-scale results, industrial adoption of cold plasma remains limited due to challenges related to scalability, process optimization, quality preservation, and regulatory acceptance. This review critically examines current knowledge on cold plasma technology in food processing, highlighting its mechanisms, applications, benefits, limitations, and future research needs.



Characteristic violet or bluish glow (“purple lightning”) observed during atmospheric cold plasma generation, resulting from excitation of nitrogen molecules (Surowsky *et al.*, 2015).

Fundamentals of Cold Plasma Technology

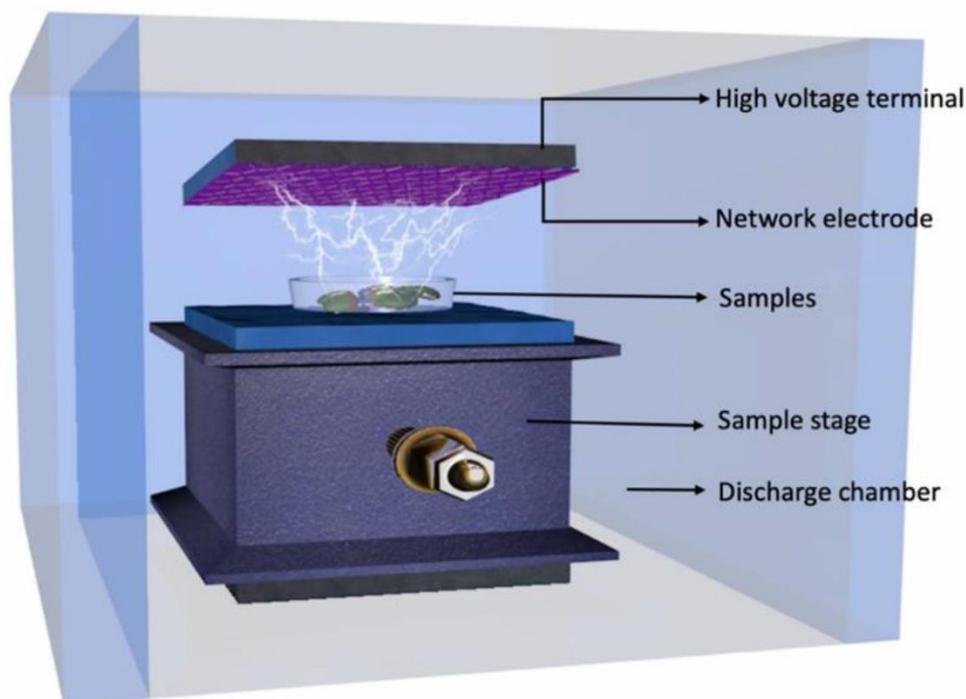
Plasma is often described as the fourth state of matter, created through the provision of adequate energy to a gas to cause partial or complete ionization. Cold plasma, also described as non-thermal plasma, is characterized from thermal plasma by the great temperature nonequilibrium between electrons and heavy particles. Though electrons have high kinetic energy, the bulk gas remains at close to ambient temperature; this allows for safe application to biological and food materials Niemira, B. A. (2012).

Cold plasma can be generated using several electrical discharge configurations including DBD, APPJ, corona discharge, and gliding arc systems. Niemira, B. A. (2012). Among those, DBD and plasma jet systems are the most widely investigated for food processing applications due to their stability, flexibility, and compatibility with atmospheric conditions. Atmospheric cold plasma systems are of particular interest for industrial applications due to the fact that there will be no requirement of vacuum chambers and thus can be easily integrated into existing processing lines. Bourke *et al.*, 2017.

How we choose the working gases affects the reactivity of these gases with various materials, which in turn affects how they react to environmental factors such as moisture or temperature. Air-based plasmas produce an enormous variety of reactive nitrogen and oxygen species when compared to other gases like argon. In contrast, when producing a stable, controlled discharge with an argon

plasma, the amount of chemical reactivity produced can be fine-tuned to produce consistency in the quality of the final product. (Pankaj *et al.*, 2018). Therefore, the type and ratio of gases used in the gas composition of the working gas greatly influence: 1) Antimicrobial Effectiveness, 2) Uniformity of Treatment, and 3) The Potential Effects on Quality of Foods.

In addition, the production of atmospheric cold plasmas in nitrogen-rich and/or air-based environments often creates a bluish purple or violet colour, which is quite common and is referred to as "purple lightning". "Purple lightning" originates from the excitation and relaxation of nitrogen molecules and other atmospheric molecules (Surowsky, B., *et al.*, 2015). The colour evidence gives a visual indication that a plasma has been created and whether or not it is stable. However, the visible glow itself does not induce microbial elimination; rather, plasma installations are composed of many reactive species, charged particles, UV light and electric fields. Cold plasma treatment operates mainly as a surface treatment because the reactive species do not penetrate deeply into materials. The technology works best for cleaning the outer surfaces of solid foods and packaging materials, but it does not work well against bacteria that live inside the products. Treatment success relies on various factors which include applied voltage and frequency settings, treatment duration, electrode arrangement, gas flow rate, and distance between plasma source and food surface (Misra *et al.*, 2016). The optimization of processing conditions and achievement of consistent results requires complete knowledge of plasma physics and plasma–food interactions.



Representative cold plasma generation systems used in food processing applications, including dielectric barrier discharge (DBD) and atmospheric pressure plasma jet (APPJ) configurations (adapted from Niemira, 2012; Misra *et al.*, 2016).

Mechanisms of Microbial Inactivation

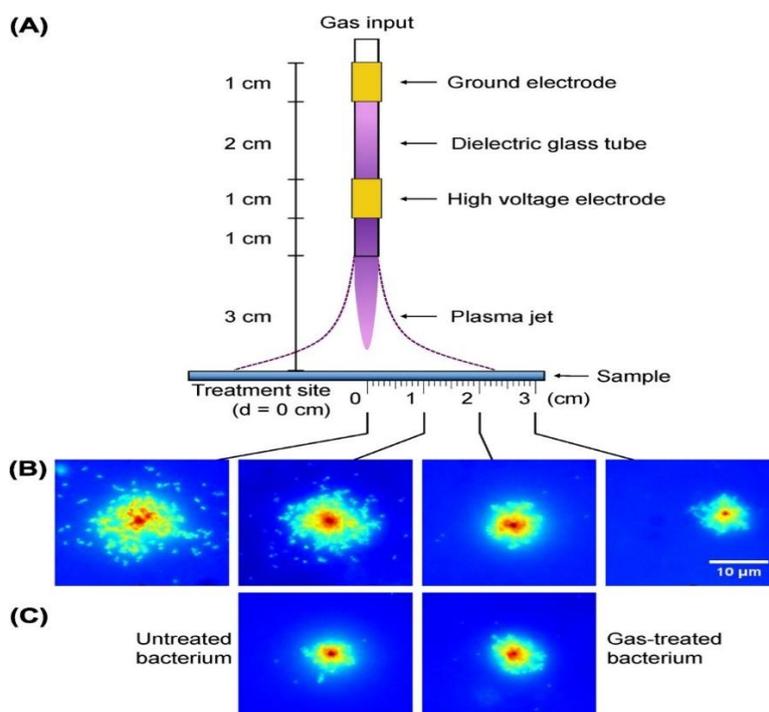
Microbial inactivation by cold plasma may be regarded as a very complex process. Chemical and physical synergism thus ensures that the progress of microbial inactivation is through the action of several agents, with the key players being ROS and RNS, which through oxidative and nitrosative

stress induce cellular damage in microbial cells (Pankaj *et al.*, 2018). These include ozone, hydroxyl radicals, superoxide anions, hydrogen peroxide, nitric oxide, and nitrogen dioxide.

One of the earliest targets of cold plasma treatment is the microbial cell envelope. ROS-induced lipid peroxidation depletes the integrity of cell membranes; increasing membrane permeability causes leakage of intracellular contents. In addition, the impairment of membrane-bound proteins minimizes necessary transport processes and impairs cellular homeostasis. Gram-negative bacteria have a thinner peptidoglycan layer, which may make cells more vulnerable to plasma-induced damage compared with Gram-positive bacteria due to their thicker cell walls.

The other major targets of plasma-generated reactive species are proteins. This is because amino acid side chains undergo oxidative modification, leading to the denaturation of proteins and inactivation of enzymes, hence a loss of metabolic function. As Bourke *et al.*, 2017 puts it, changes in this manner have serious consequences for impairment in cellular repair mechanisms and energy production, accelerating microbial death. Microbial Damage due To Exposure of Microorganisms to Cold Plasma. Cold Plasma destroys Microbial Nucleic Acids; Cold Plasma reactive elements damage Microbial DNA both by Generation of Reactive Oxygen Species (ROS) and Ultraviolet (UV) Radiation.

Bacteria (and other Microbial Life Forms) are especially resistant to Cold Plasma Treatment. This is because the very Structure or Surface features of Bacterial Spores or Biofilms provide additional Protection, in addition to the fact that the Environmental conditions were Optimized for All Cold Plasma Treatments, including Surfaces and Physical Characteristics of Bacterial Spores, and Biofilms. Furthermore, certain types of Treatment Parameters (including Length of Treatment, Atmospheric Composition, etc.) have Higher Thresholds than has been studied, thus Resulting in a Greater Susceptibility to Being Killed or Stopped by Cold Plasma Application.



Schematic illustration of microbial inactivation mechanisms induced by cold plasma, including reactive oxygen and nitrogen species (ROS/RNS), membrane disruption, protein oxidation, and DNA damage (Bourke *et al.*, 2017; Pankaj *et al.*, 2018).

Applications in Fruits and Vegetables

Cold plasma technology is one of the emerging technologies that have been widely used in the decontamination and preservation of fresh fruits and vegetables, the most critical food commodities that are susceptible to microbial infection. Fresh produce typically bears irregular surfaces, natural wax layers, and microscopic crevices that favour the growth of pathogenic and spoilage microorganisms. Cold plasma treatment has, however, been shown to significantly reduce the populations of pathogenic bacteria such as *Escherichia coli*, *Salmonella* spp., and *Listeria monocytogenes* from various produce commodities, including leafy greens, apples, strawberries, tomatoes, and peppers (Niemira, 2012; Misra *et al.*, 2016). The non-thermal nature of the technology allows efficient surface decontamination of the produce without thermal stress.

Cold plasma was identified as one of the major advantages in fruit and vegetable processing because of its capability to act as an alternative to conventional chemical sanitizers. Chlorine-based washes are indeed widely used; however, they raise concerns with respect to chemical residues and the generation of harmful disinfection by-products. Offering a residue-free approach, cold plasma reduces water consumption and, therefore, is extremely attractive both from safety and sustainability viewpoints. According to Bourke *et al.*, (2017), in addition to microbial inactivation, plasma treatment was reported to decrease pesticide residues and suppress surface enzymatic activity responsible for browning in some fruits. (Pankaj *et al.*, 2018).

While these advantages exist, the effectiveness of treatments is greatly impacted by physical structure of the surface area, different types of produce, and intensity of each treatment. Too much time spent in the plasma field may dehydrate, change the colour, or soften the texture of a delicate product (for example, berries and leafy greens). This is why food-specific optimization of plasma processing parameters is important to maximize the safety of the produce by eliminating pathogenic microorganisms, while still retaining the characteristics of a fresh product.

Applications in Meat and Poultry

Meat and poultry products are major contributors to foodborne illness globally because these foods often harbour foodborne pathogens like *Salmonella* spp., *Campylobacter jejuni*, and *Listeria monocytogenes*. Cold plasma technology is one of the most investigated surface decontamination techniques for both raw and processed meat products, particularly since the contamination typically remains confined to the surface layers of these foods. Researchers have shown significant microbial reduction on poultry carcasses, chicken breasts, beef steaks, and minced meat after cold plasma treatment.

Unlike conventional chemical decontamination methods, cold plasma does not leave residual compounds on meat surfaces, enhancing consumer acceptance and meeting clean-label trends. Plasma treatment can also be performed post-slaughter or post-processing, thus offering flexibility within existing meat processing workflows. Additionally, the short duration of the treatments avoids any temperature rise that would lead to structural changes in muscle tissues.

However, for meat and poultry applications, lipid oxidation remains a major limitation. The occurrence of an oxidative reaction in lipids might be initiated through the reactive oxygen species produced, resulting in discoloration, off-odor, and shorter storage life. The studies suggest that modified atmosphere plasma treatments, reduced oxygen environments, and controlled exposure times can minimize those effects to some extent. Therefore, balancing microbial inactivation with oxidative stability remains a critical challenge for commercial adoption in meat processing.

Applications in Seafood

Seafood products are highly perishable due to their high moisture content, neutral pH, and abundance of unsaturated fatty acids. Cold plasma is a promising non-thermal method that has been applied to seafood in an effort to extend shelf life by reducing surface microbial loads without compromising freshness. Reductions in spoilage microorganisms and foodborne pathogens have been reported for fish fillets, shrimp, oysters, and shellfish following plasma treatment.

Cold plasma treatment reduces microbial growth during refrigerated storage and increases overall shelf life along with better safety. Because seafood quality is strongly linked with attributes like texture, odour, and appearance, the non-thermal nature of plasma is exceptionally helpful. However, seafood lipids are highly prone to oxidation, and plasma-induced reactive species may accelerate oxidative rancidity if treatment conditions are not optimized appropriately. Such plasma parameters, like shorter exposure times and environments with an inert gas, would minimize deterioration in quality. While strong potential is revealed by these studies conducted in the laboratory, further research will be required aimed at assessing any long-term storage effects and consumer sensory perceptions of seafood products treated with plasma.

Applications in Cereals, Nuts, Seeds and Spices

Cereals, nuts, seeds, and spices are very often contaminated with the fungal spores and mycotoxin, producing molds mainly because of their long storage periods and exposure to humid environments. The use of conventional thermal decontamination methods is usually out of the question for these low, moisture products as such methods can change flavour, aroma, and functional properties. Cold plasma has been evaluated as a possible solution to microbial and mycotoxin contamination in dry food matrices (Thirumdas, R., *et al.*, 2015).

Plasma treatment has been a successful method to eventually lead fungal spores to inactivation and to lower mycotoxin levels on the surfaces of grains and spices without the increase in moisture content and without the occurrence of structural damage (Misra *et al.*, 2016). The low water activity that these products have is what makes plasma more effective as the reactive species are kept active on dry surfaces for longer periods.

Nevertheless, the problem of uneven exposure arising from complex surface geometry and bulk handling still exists. There have been suggestions of continuous, flow and fluidized, bed plasma systems to overcome the issue of treatment uniformity. In general, the use of cold plasma is very close to being a viable solution to the problem of safety in dry food commodities and at the same time, maintaining their quality attributes.

Effects on Food Quality and Nutritional Attributes

Preserving food quality and nutritional value should be the most important factor when assessing cold plasma technology. A major part of these studies had reported a minimal change in colour, texture, and some other sensory attributes when plasma treatment conditions were optimized (Bourke *et al.*, 2017). Since technology works at almost ambient temperatures, heat, sensitive vitamins, and bioactive compounds are normally preserved better than in the case of thermal treatment (Pankaj *et al.*, 2018).

However, plasma, induced oxidative reactions may affect some quality parameters. Lipid oxidation is the most significant issue in meat, seafood, and nut products that are rich in fats, where reactive oxygen species can cause the rancidity to progress rapidly (Misra *et al.*, 2016). Protein oxidation has

been recorded as well, which may result in proteinaceous materials becoming unstable in solubility and water, holding capacity.

The variations in pigments like chlorophyll, myoglobin, and carotenoids may affect colour stability depending on the factors such as the intensity of the treatment and the type of the food that is treated. These impacts demonstrate how important it is to adjust plasma parameters for the food matrix. There are only a few long, term storage experiments, and it is further research that is required to assess nutritional and sensory attributes' stability over a longer shelf life.

Cold Plasma in Food Packaging

One of the most common uses of cold plasma technology is surface modification of food packaging materials. Polymer films treated with plasma can adsorb more readily because their surface energy is raised by the treatment with plasma, generated radicals, pigments, and barrier layers (Niemira, 2012). Such a change can have a positive effect on the proceeding of packaging without changing the properties of the bulk material.

Treatment with cold plasma in the packaging is a real breakthrough in the field of food safety after sealing the product. The plasma, generated reactive species travel through the package headspace and surface contamination is thus lowered without any recontamination from the post, processing step (Bourke *et al.*, 2017). The technique is extremely effective in the case of ready, to, eat products and minimally processed foods.

Meanwhile, research is going on in the field of plasma, assisted antimicrobial coatings and functional packaging systems. But on the other hand, issues related to compatibility of the materials, permeability of the gases, and possible chemical reactions must be solved first. The safety and regulatory compliance of plasma, treated packaging materials should always be at the forefront of research efforts (Misra *et al.*, 2016).

Industrial Scale-Up and Regulatory Considerations

The main issues which hinder the promotion of cold plasma technology from the lab to the mass production scale are technical ones as well as strict regulations. The main concern in this case is how to ensure a uniform plasma treatment of a large product volume, especially in the case of continuous processing systems (Niemira, 2012). Scalability and the cost of operation greatly depend on how the plant is built, the design of the electrodes and the efficiency of the energy use.

Considering the matter from the regulatory angle, cold plasma is still a new processing technology in most parts of the world. Regulators demand thorough safety testing to be done before the technology is adopted, including the evaluation of possible chemical by, products and changes in food composition (Bourke *et al.*, 2017). Now, the absence of globally harmonized regulations is the main reason for limited commercial applications of this technology.

It is therefore very important for researchers, industry players, and regulators to work together very closely to create standardized validation protocols and guarantee consumer safety.

Research Gaps and Future Research Directions

Despite significant advancements, there are still several research gaps that prohibit the widespread commercial application of cold plasma technology. The lack of uniform processing parameters is a major drawback that makes it extremely challenging to compare data from trials and various food matrices (Misra *et al.*, 2016). To obtain microbial inactivation that is effective and does not degrade the product's quality, many food products need optimization techniques.

There are very few long, term storage studies that examine nutritional stability, sensory attributes, and consumer acceptance. Furthermore, most of the studies are still at the laboratory stage, with only a few pilot, scale, and industrial trials. Studies on the economic feasibility of the technology, life, cycle assessments, and evaluations of energy efficiency are also few and far between in the literature.

Research to be done in the future should include on, line process monitoring, sophisticated plasma source design, coupling with smart packaging systems, and regulatory harmonization. It will be necessary to fix these holes if the cold plasma technology is to be turned into a practical way of preserving food that can be sold in the market.

Conclusion

Cold plasma technology is emerging as a robust and adaptable non, thermal preservation method that can meet the major challenges that the food industry of the 21st century faces. The distinctive violet or bluish glow often called “purple lightning” visually represents this technology. It entails the use of energetic plasma chemistry along with low temperatures of processing; hence it is a heat, sensitive product of the food industry that benefits the most from it. By the generation of reactive oxygen and nitrogen species, ultraviolet photons, and localized electric fields, cold plasma can kill a large variety of pathogens and microorganisms that cause food spoilage without the food product being heated to any significant extent.

This work served as a reminder to the vast potential that cold plasma technology holds for treating almost any kind of food, such as fresh fruits and vegetables, meat and poultry, seafood, and for dry foodstuffs such as cereals, nuts, seeds, and spices. Besides direct treatment of foods, cold plasma technology has a promising future in food packaging, where it can upgrade material performance, post, processing contamination can be eliminated, and the packaging can serve as a reservoir for active and in, package preservation systems. If the cold plasma treatment is suitably optimized, the sensory properties of foods and their nutritional quality will be largely maintained, which is in line with the consumers’ wishes for fresh, like and minimally processed products.

On the other hand, problems of process optimization, scalability, as well as regulatory acceptance, need to be solved before cold plasma can be successfully taken from the laboratory research stage to industrial practice. The diversity of plasma systems, food matrices, and treatment conditions makes it difficult to establish standardized protocols and to carry out comprehensive safety assessments. Besides that, long, term storage experiments and consumer acceptance studies are very important to confirm that this new technology is commercially feasible.

In general, cold plasma is an example of “purple lightning” preservation which is a promising and environmentally friendly breakthrough in food processing. Cold plasma has the potential to become a major part of future food preservation strategies if there is a continued effort in interdisciplinary research, technological improvements, and cooperation between the academic community, industry, and regulatory bodies. This will help food safety, quality, and sustainability to be guaranteed in the global food supply.

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COMMUNITY-BASED AQUACULTURE DEVELOPMENT IN CHHATTISGARH

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Abstract

Chhattisgarh has enormous potential for the growth of aquaculture due to its abundance of freshwater resources. By including nearby farmers and rural communities in the joint management of ponds and tanks, community-based aquaculture provides a sustainable and inclusive method of fish farming. Shared resources, group decision-making, and the use of contemporary aquaculture methods including polyculture, biofloc systems, and environmentally friendly practices are all highlighted in this paradigm. In addition to increasing fish output, the strategy empowers women and other marginalized groups, fosters skill development, and offers a reliable source of income. Community-based aquaculture contributes to rural livelihood security while preserving environmental sustainability through resource optimization and social harmony. Government support and extension services are necessary to solve issues like funding, member coordination, and technical training. All things considered, community-driven fish farming is a viable approach to Chhattisgarh's rural development and sustainable aquaculture expansion.

Key Words: Community based Culture, Social impact, Rural Livelihood, Resource management

Introduction

Chhattisgarh is often referred to as the "rice bowl of India," but the state is equally rich in freshwater resources that support aquaculture. With thousands of ponds, tanks, reservoirs, rivers, and seasonal water bodies, fish farming has emerged as an important livelihood activity for rural and tribal communities. Traditionally, aquaculture in the state has been practiced at a small scale, mainly for household consumption or limited local markets. However, growing demand for fish, rising awareness about nutrition, and government support have created new opportunities for expanding aquaculture production in a sustainable way. An inventive strategy that unites farmers to jointly oversee fish farming operations is community-based aquaculture. Villagers create groups or cooperatives to share resources, expertise, and duties rather than working alone. In Chhattisgarh, where a large number of water bodies are owned or run by local organizations, this strategy is especially appropriate. By working together, farmers may use superior technologies such scientific stocking techniques, better feed management, and composite carp culture, which will increase output and lower expenses. Community-based aquaculture is essential for social development in addition to its economic advantages. It boosts local collaboration, generates job possibilities, and promotes women's and marginalized groups' involvement. Additionally, community management encourages ecologically conscious behavior, which lowers overexploitation and preserves water quality.

Community-Based Aquaculture: A Collective Approach

In community-based aquaculture, local groups collaborate to oversee fish farming operations in shared or jointly owned bodies of water. This strategy blends in well with the current social structure

in Chhattisgarh, where village panchayats or community organizations oversee a large number of ponds, tanks, and reservoirs. Community members work together to prepare ponds, supply high-quality fish seed, feed fish, control water, and harvest fish rather than individual farmers working alone. This communal framework promotes the adoption of scientific aquaculture practices and lowers individual financial risk. Farmers can reduce production costs and increase overall efficiency by pooling resources including feed, equipment, and technical expertise. Additionally, training programs offered by research institutes and fisheries agencies help community organizations better grasp disease prevention, sustainable management techniques, and improved carp culture. Community-based aquaculture fosters social cooperation and mutual responsibility among villagers in addition to financial benefits. By involving women, young people, and underprivileged groups, it encourages inclusive involvement, which supports livelihood security and social empowerment. Community-driven fish farming is a sustainable strategy to improve income, nutrition, and environmental stewardship in a state like Chhattisgarh, where rural and tribal inhabitants rely significantly on natural resources.

Economic and Social Impact on Rural Livelihoods

In Chhattisgarh, community-based aquaculture has become a potent instrument for enhancing rural livelihoods. It helps rural households lessen their reliance on seasonal crops by offering a steady source of income. Fish farming is particularly advantageous for small and marginal farmers since it provides quicker returns than many traditional crops. Collective practice ensures a more equitable allocation of revenue within the community by sharing profits among members. This strategy greatly advances social development in addition to the economy. At the village level, collective fish farming improves trust, collaboration, and decision-making. Activities including feed preparation, seed rearing, harvesting, and local fish marketing have given women's self-help groups additional options. In addition to raising household income, this involvement boosts women's self-esteem and social standing. Additionally, by expanding the supply of reasonably priced, fresh fish—a rich source of protein and vital micronutrients—community aquaculture enhances nutritional security. Consuming fish on a regular basis helps combat malnutrition, particularly in children and other susceptible populations. Community-based aquaculture contributes significantly to inclusive and sustainable rural development in Chhattisgarh by generating revenue, creating jobs, and improving nutrition.

Environmental Sustainability and Resource Management

One of Chhattisgarh's community-based aquaculture's main advantages is its environmental sustainability. There is more accountability for preserving ecological balance and water quality when water bodies are administered jointly. Environmentally friendly practices include scientific stocking density, appropriate feed management, and minimal chemical use are frequently adopted by communities. These methods guarantee the long-term productivity of ponds and reservoirs by lowering water pollution and preventing disease outbreaks. Additionally, community management promotes the preservation of natural resources. Aquatic habitats are kept healthy through timely harvesting, weed eradication, and routine water quality monitoring. A balanced approach to resource usage is achieved in many villages by fusing traditional knowledge with contemporary aquaculture methods. This integration maintains fish output while promoting biodiversity. Community-based aquaculture provides resilience against environmental uncertainties including unpredictable rainfall and water scarcity in the context of climate change. Communities can quickly adapt by changing species selection, water use, and stocking schedules thanks to shared decision-

making. Therefore, in Chhattisgarh, community fish farming not only sustains livelihoods but also encourages prudent resource management and environmental stewardship.

Conclusion

Chhattisgarh has a lot of potential for aquaculture because it has an abundance of freshwater resources, such as ponds, tanks, rivers, and reservoirs. A sustainable and inclusive method, community-based aquaculture involves local farmers and village groups working together to manage fish farming operations. Communities share tasks including pond preparation, feeding, water management, harvesting, and planting high-quality fish seed instead of working alone. In addition to lowering production costs and individual financial risk, this cooperative structure promotes the use of cutting-edge methods including polyculture, biofloc systems, and scientific feeding practices. Beyond financial gains, it fosters social cohesiveness and empowers women, young people, and underrepresented groups by giving them opportunity to generate income and actively participate in decision-making. While community-managed ponds encourage ecologically conscious behaviors, biodiversity conservation, and effective resource management, regular fish production enhances household nutrition and food security. Government assistance and extension services can help get beyond obstacles like initial investment requirements, technical training requirements, and member cooperation. All things considered, community-based aquaculture in Chhattisgarh provides a comprehensive approach to rural development by fusing environmental sustainability, social empowerment, and livelihood enhancement, making it a resilient and inclusive model for the future.

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DESIGNER MICROBES: THE FUTURE OF ECO-FRIENDLY FARMING**J. R. Patel^{1*} and K. J. Patel²**¹Department of Agricultural Microbiology, N. M. College of Agriculture, NAU, Navsari, Gujarat, India²Department of Agricultural Microbiology, B. A. College of Agriculture, AAU, Anand, Gujarat, India*Corresponding Email: jhanavipatel6629@gmail.com**Abstract**

CRISPR-based genome editing has opened an unprecedented frontier in agricultural microbiology, enabling scientists to precisely modify beneficial microbes that support plant nutrition, growth and disease resistance. Traditional microbial inoculants such as nitrogen-fixing bacteria, phosphate-solubilizing microbes and biocontrol fungi have long supported sustainable farming, but their performance is often inconsistent under field conditions. CRISPR allows targeted enhancement of metabolic pathways responsible for nutrient acquisition, hormone production, and pathogen inhibition, creating more robust and responsive microbial strains. Engineered nitrogen fixers with enhanced *nif* gene regulation, phosphate-solubilizing bacteria with optimized organic acid secretion and biocontrol microbes with strengthened antifungal or anti-nematode mechanisms are now emerging as next-generation agricultural tools. This article explores the science behind CRISPR-edited microbes, recent breakthroughs, potential risks, regulatory concerns and how these designer microbes may contribute to higher yields, reduced fertilizer use and improved soil health. Together, they represent a promising step toward climate-smart, resource-efficient farming.

Keywords: CRISPR, beneficial microbes, sustainable agriculture, biofertilizers, biocontrol**The Beginning of a Microbial Revolution**

The story of agricultural innovation has always been rooted in the microscopic world. Long before synthetic fertilizers existed, plants relied entirely on soil microbes to supply nutrients, protect roots and stabilize soil ecosystems. Today, as the demand for sustainable farming intensifies, the spotlight has returned to these tiny allies but with a powerful new tool in hand: CRISPR-Cas genome editing. CRISPR, originally a bacterial immune system, has become one of the most transformative technologies in modern biology, allowing scientists to precisely cut, modify, or insert genes. When applied to agricultural microbes, CRISPR opens the door to designing supercharged microbial inoculants that can outperform naturally occurring strains. These engineered microbes promise to reduce chemical fertilizers, suppress crop diseases and help farmers adapt to climate-driven challenges all while improving soil health.

This is not science fiction. Gene-edited microbial strains are already under development in labs across the world. From strengthened nitrogen-fixing bacteria to high-efficiency biocontrol fungi, CRISPR is catalyzing a new era of sustainable agriculture.

Why Edit Microbes? The Limitations of Natural Strains

Traditional microbial inoculants such as *Rhizobium*, *Azotobacter*, *Bacillus*, *Pseudomonas* and *Trichoderma* are widely used in biofertilizers and biopesticides. However, they face several limitations:

- Field performance is inconsistent due to temperature fluctuations, soil pH, salinity and competition with native microbes.
- Nutrient uptake pathways are naturally slow or weak.
- Many microbes lose activity once commercialized or after storage.
- Biocontrol microbes do not always colonize plant roots sufficiently to suppress pathogens.

CRISPR allows scientists to upgrade these microbes by enhancing the pathways responsible for nutrient solubilization, plant hormone production or pathogen suppression without altering their essential microbial identity.

CRISPR-Edited Nitrogen Fixers: Reducing Fertilizer Dependency

Chemical nitrogen fertilizers account for nearly 40% of global agricultural emissions. Biological nitrogen fixation offers a clean alternative, but natural N-fixing microbes often struggle under field conditions.

How CRISPR Improves N-Fixing Bacteria

Researchers are editing microbes like *Rhizobium*, *Azospirillum* and *Azotobacter* to:

- Strengthen *nif* gene expression (nitrogenase complex)
- Increase oxygen tolerance of the nitrogenase enzyme
- Enhance root colonization genes
- Reduce energy costs of nitrogen fixation
- Introduce pathways enabling nitrogen fixation in non-legumes

For example, scientists have used CRISPR to delete repressor genes that limit nitrogenase activity, resulting in higher continuous nitrogen fixation even under stress. Other groups are inserting nitrogen-fixing gene clusters into plant-associated bacteria that naturally colonize cereals such as maize, wheat, and millets.

Impact on Farming

- 20–40% reduction in urea usage
- Higher nitrogen-use efficiency in crops
- Reduced soil and water pollution

Phosphate-Solubilizing Microbes: Unlocking Earth's Hidden P

Only 1–2% of soil phosphorus is available to plants. Phosphate fertilizers are costly, environmentally damaging, and sourced from finite mineral reserves.

Naturally occurring phosphate-solubilizing bacteria (PSB) like *Pseudomonas*, *Bacillus* and *Enterobacter* release organic acids to convert insoluble phosphate into plant-available forms. However, their efficiency remains modest.

CRISPR Enhancements in PSB

Using CRISPR, scientists can:

- Overexpress genes for gluconic acid and other P-solubilizing organic acids
- Improve tolerance to alkaline soils
- Strengthen root attachment through biofilm-forming genes
- Modify regulatory genes to maintain phosphate solubilization even at high nutrient levels

One notable study edited *Bacillus subtilis* to enhance the **pqq** gene cluster responsible for organic acid production, significantly increasing soil P availability in wheat fields.

Impact on Farming

- Reduced need for rock phosphate
- Improved crop growth in P-deficient soils
- Better root development and early seedling vigor

Biocontrol Microbes: CRISPR as a Biological Pest Shield

Biocontrol microbes like *Trichoderma*, *Bacillus*, and *Pseudomonas* produce antibiotics, enzymes, and secondary metabolites that suppress plant pathogens. But natural strains have variable efficacy.

CRISPR Advances for Biocontrol

Researchers are editing biocontrol agents to:

- Increase production of antifungal compounds
- Enhance production of siderophores that starve pathogens of iron
- Improve competition with pathogens in the rhizosphere
- Add genes to target nematodes and soil-borne diseases
- Remove genes that slow down root colonization

For example, CRISPR-edited *Trichoderma harzianum* strains now produce higher levels of chitinases and glucanases, making them more effective against *Fusarium* and *Rhizoctonia*.

Impact on Farming

- Reduced chemical pesticide use
- Stronger crop immunity
- Lower post-harvest losses

How Safe Are CRISPR-Edited Microbes?

Safety and regulation are central concerns. Unlike GMOs, CRISPR edits do not necessarily add foreign DNA—they often modify existing genes. Some countries classify such microbes as non-GMO if no external DNA remains. Still, issues remain:

- Potential transfer of edited genes to native microbes
- Competition with natural microbial communities
- Long-term ecological effects

Current research focuses on designing **gene-lock systems**, self-destruct genes, and containment strategies to ensure environmental safety.

Future Prospects: Microbial Consortia and Smart Biofertilizers

The next generation of designer microbes is expected to integrate synthetic biology, machine learning, and microbiome engineering.

Emerging Trends

- **Multiplex CRISPR editing:** Simultaneous modification of multiple gene clusters for enhanced performance.
- **Synthetic microbial consortia:** Co-designed communities of bacteria, fungi, and cyanobacteria for holistic nutrient cycling.
- **AI-guided strain optimization:** Computational prediction of beneficial genetic modifications.
- **Smart delivery systems:** Encapsulation technologies ensuring microbial survival under field stresses.

Conclusion

CRISPR-edited microbes represent a promising innovation in modern agriculture, offering precise and sustainable solutions to rising fertilizer costs, climate stress, and soil degradation. Unlike traditional biofertilizers with inconsistent field performance, CRISPR enables targeted enhancement

of beneficial microbial traits, improving nutrient availability, disease suppression, and crop stress tolerance. Engineered microbes can be optimized for nitrogen fixation, phosphate solubilization, and biocontrol while maintaining ecological balance. As climate change intensifies drought, salinity, and pathogen pressure, these microbes provide an environmentally responsible alternative to chemical inputs. Despite regulatory and biosafety challenges, continued research is improving their reliability and safety. Overall, designer microbes hold strong potential to support climate-smart, resource-efficient, and sustainable global food production.

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CROP IDEOTYPES: DESIGNING PLANTS FOR FUTURE AGRICULTURE

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Abstract

Crop ideotype is a model plant designed with specific traits to perform in a particular set of environmental conditions efficiently. It mainly focuses on developing plants with high yield by improving various morphological and physiological traits. In the present scenario of drastic climate change, limited resources and increasing food demand, ideotype breeding gained importance in modern agriculture. It integrates conventional breeding with advanced molecular techniques and has become a promising solution for future agriculture. Moreover, ideotype breeding facilitates the development of climate-resilient cultivars with improved tolerance to biotic and abiotic stresses. This approach enhances productivity while minimizing input requirements, thereby promoting sustainable and resilient agricultural systems.

Key words: Ideotype, individual trait, yield, breeding, variety

Ideotype

An ideotype is a biological model that is anticipated to function or react predictably in a particular environment. The concept of ideotype was first proposed by Donald (1968) while working on wheat. More accurately, an ideotype is a model plant which could produce a greater quantity of grain, oil, fibre, and other useful products under specific environmental conditions. The plant needs some requirements to withstand prevailing environmental conditions to produce in a better manner, which could be achieved through the ideotype concept. "Ideotype breeding" is the process of breeding plants with the features that would ensure their ability to adapt to particular climatic conditions and produce higher yields. It can also be described as a plant producing dry matter per unit of input. Ideotype gives an illustration of the key qualities crop plants should have.

The difficulties faced by modern agriculture, such as the rising global food demand, shifting climatic conditions, and scarce resources, have led to the necessity of developing plants through ideotype breeding. Ideotype breeding offers a remedy by offering a methodical and focused strategy for creating crop varieties with certain features that maximise performance under certain circumstances. Using ideotype breeding, crops can be developed more productively, resiliently, and sustainably by being tailored to their intended conditions. In order to create varieties that can maximise productivity even in areas with a limited supply of resources, ideotype breeding focuses on choosing and combining features including high yield potential, improved nutrient usage efficiency, and greater stress tolerance. Ideotype breeding is a possible solution to tackle the various difficulties of contemporary agriculture and support the sustainable production of food by fusing conventional breeding techniques with cutting-edge technologies.

Main features of crop ideotype breeding

1. Emphasis on individual trait

2. Includes yield-enhancing traits
3. Exploits physiological variation
4. Slow progress
5. Selection
6. Designing a model
7. Interdisciplinary approach
8. A Continuous process

Steps in ideotype breeding

The breeding procedure includes four important steps,

Development of the conceptual model: A conceptual theoretical model is created by specifying the values of numerous morphological and physiological features. For instance, measurements of plant height, maturity period, leaf size, leaf number, leaf angle, photosynthetic rate, etc. are provided. After then, attempts are undertaken to realise this concept.

Selection of base material: After developing the conceptual model of the ideotype, choosing the foundation material is a crucial step. To be employed in creating a model plant type, genotypes should have a broader genetic range and greater adaptability. The global gene pool of the concerned crop species is used to select genotypes for plant stature, maturity duration, leaf size and angle, and resistance.

Incorporation of the desired trait: The process of integrating multiple physical and physiological features from various genotypes into a single genotype is the next crucial step. Most field crops use a variety of breeding techniques, including single crosses, three-way crosses, multiple crosses, backcrosses, composite crossing, intermating, mutation breeding, heterosis breeding, etc., to generate perfect plant kinds.

Selection of ideal plant type: To create the desired plant type, plants with the ideal morphological and physiological features are chosen in segregating populations and interbred. Visual observations are used to evaluate morphological characteristics, and sophisticated tools are used to capture physiological measures.

Genetic improvement strategies through ideotype breeding

Various genetic improvement techniques are used in ideotype breeding to create crop types with desired features (Peng *et al.*, 2008). These tactics emphasise gene selection and combination using conventional breeding techniques or advanced technology.

- 1) **Conventional breeding:** In order to produce new genetic combinations, this tactic entails crossing and choosing plants with desirable features. Typically, the procedure starts with phenotypic selection based on agronomic or visual features, then several generations of breeding to incorporate the desired traits in the population.
- 2) **Hybridization:** Hybrid breeding is used to take advantage of heterosis, also known as hybrid vigour, in which the offspring of crossings between two genetically distinct parents perform better than either parent alone.
- 3) **Molecular marker-assisted selection (MAS):** In order to speed up the breeding process, MAS makes use of genetic markers connected to traits. Breeders can choose individuals that have the desired qualities more effectively and precisely by using marker-assisted selection.
- 4) **Genomic selection:** Genomic selection makes use of high-throughput genotyping and phenotyping to forecast an individual's breeding value based on their entire genome.

- 5) **Genetic engineering:** Specific genes relevant to desired qualities can be introduced or modified using genetic engineering techniques, such as transgenic methods or genome editing tools like CRISPR-Cas9. Through this procedure, it is possible to precisely alter plant genomes to produce features that may be difficult to obtain through traditional breeding techniques.

Technologies and tools in ideotype breeding : The efficiency, accuracy, and effectiveness of the breeding processes are all improved using various technologies and instruments in ideotype breeding (Gosa *et al.*, 2019).

- 1) **Molecular markers:** To find specific DNA sequences linked to desirable qualities, molecular markers like Single Nucleotide Polymorphisms (SNPs) and Simple Sequence Repeats (SSRs) are utilised. They make it easier for breeders to recognise and choose individuals with the necessary alleles or gene combinations.
- 2) **Next-generation sequencing (NGS):** The sequencing of whole genomes can be done quickly and affordably with NGS methods. They offer useful genomic data, including genetic variants, patterns of gene expression, and regulatory components. Breeders can use NGS to investigate the genetic underpinnings of complex characteristics, find novel genes or QTLs (Quantitative Trait Loci), and create genomic resources for targeted trait enhancement.
- 3) **Genomic selection:** Genomic Selection combines high-throughput genotyping and phenotyping data to forecast an individual's breeding value based on their genome. Breeders can simultaneously estimate the genetic potential of plants for a variety of qualities by using statistical models and machine learning techniques.
- 4) **High-throughput phenotyping:** Technologies for high-throughput phenotyping allow for the quick and non-destructive monitoring of a variety of plant properties. Aspects like plant height, canopy structure, leaf area, photosynthetic efficiency, and disease signs can all be measured using methods like remote sensing, imaging, and robotics-based platforms.
- 5) **Genome editing technologies:** Specific DNA sequences in the plant genome can be precisely modified using genome editing tools like CRISPR-Cas9. By adding or changing genes linked to desirable features, they offer a potent tool for improving certain traits.
- 6) **Bioinformatics and data analytics:** By organising and analysing massive genetic and phenotypic databases, bioinformatics and data analytics are crucial in ideotype breeding. Breeders can use these techniques to gather insightful information, find potential genes or QTLs, and forecast trait performance.

Ideotype breeding can increase the efficiency of the breeding process overall and speed up the production of crop varieties with specific features by utilising these technologies and techniques (Varshney *et al.*, 2021).

Merits of ideotype breeding

- i. It takes advantage of the morphological and physiological variance
- ii. Experts in the fields of plant breeding, physiology, biochemistry, entomology, and plant pathology are involved in ideotype breeding.
- iii. Different morphological and physiological characteristics are stated in this breeding process, and each character or trait helps to increase yield.
- iv. It is a reliable approach to creating cultivars for a certain environment or situation.
- v. Ideotype breeding combines desirable genes for several qualities from many sources into a single genotype to provide solutions to multiple problems at once, such as disease, pest and lodging resistance, maturity duration, yield, and quality.

Demerits of ideotype breeding

- i. It is challenging to combine multiple desired physiological, morphological, and disease-resistance features from different sources into a single genotype
- ii. Ideotype breeding takes longer to generate cultivars than traditional breeding, which focuses on improving yield and one or two other qualities.
- iii. Ideotype breeding cannot replace conventional or traditional breeding. It complements the earlier.
- iv. Ideotypes are dynamic objects that alter in response to new information, demands, national policies, etc.

Conclusion

Ideotype breeding is a targeted approach to design crop plants with specific traits to improve yield and nutritional use efficiency. Its main purpose is to develop resilient and high-performing varieties suited to climatic conditions. In the era of climate change, it will hold a significant position in future. Thus, ideotype breeding represents a sustainable pathway to ensure food security and agricultural resilience in the coming decades.

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KITCHEN GARDEN FOR NUTRITIONAL SECURITY

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Abstract

A kitchen garden plays a crucial role in achieving nutritional security by ensuring a continuous supply of fresh, diverse, and nutrient rich food at the household level. By cultivating vegetables, fruits, and herbs such as leafy greens, legumes, roots, and spices within available home spaces, families can significantly improve the quality of their diets. Kitchen gardens help combat micronutrient deficiencies often referred to as hidden hunger by providing vitamins, minerals, and antioxidants essential for good health. They also reduce dependence on market produce, which may be expensive, seasonal, or contaminated with chemical residues.

In addition to improving nutrition, kitchen gardens promote food self-reliance and sustainable living. They encourage the use of organic waste for composting, efficient water use, and environmentally friendly pest management practices. Kitchen gardening is suitable for both rural and urban households, including small spaces such as backyards, terraces, and balconies. Beyond physical health benefits, it fosters awareness about healthy eating, strengthens family involvement in food production, and contributes to long-term household resilience and well-being.

Why nutritional security is important

Nutritional security is vital because it extends beyond mere food availability to ensure consistent access to safe, diverse, and nutrient-rich diets that meet the physiological needs of individuals at all stages of life. Adequate nutrition is fundamental for maintaining physical health, as it helps prevent undernutrition, micronutrient deficiencies, and diet-related non-communicable diseases such as obesity, diabetes, and cardiovascular disorders. In children, nutritional security supports optimal growth, cognitive development, learning capacity, and immunity, thereby reducing morbidity and long-term healthcare costs. For adults, it enhances work efficiency, mental well-being, and overall productivity, contributing directly to economic growth and national development.

From a social perspective, nutritional security plays a crucial role in reducing inequalities, as vulnerable populations—including women, children, and the elderly—are disproportionately affected by poor dietary access and quality. Rising food prices, particularly for vegetables and other nutrient-dense foods, often compel low-income households to rely on inexpensive, ultra-processed foods that lack essential vitamins and minerals. Such dietary compromises can result in malnutrition, including stunting and wasting among children, thereby perpetuating intergenerational cycles of

poor health and poverty. Furthermore, nutritional security is closely linked to sustainable food systems, agricultural biodiversity, and environmental health, as balanced diets depend on resilient ecosystems and responsible resource management. In the long term, ensuring nutritional security strengthens human capital, improves resilience to health and economic shocks, and is essential for achieving sustainable development goals and fostering healthier, more equitable societies.

Nutritional security also plays a critical role in strengthening community resilience and public health systems. Well-nourished populations are better equipped to withstand health emergencies, infectious disease outbreaks, and economic disruptions, as adequate nutrition enhances immune function and recovery capacity. Community-level initiatives such as kitchen gardening, school nutrition programs, and local food production systems can improve access to fresh and nutritious foods while promoting dietary diversity and food sovereignty. These approaches not only reduce dependence on market fluctuations but also empower households with knowledge and skills to make healthier food choices. By integrating nutrition-sensitive agriculture, education, and social protection programs, governments and institutions can address the root causes of malnutrition in a sustainable manner, ensuring long-term nutritional well-being and societal stability.

Role of kitchen garden in nutritional security

Kitchen gardens play a significant and multifaceted role in achieving nutritional security by ensuring continuous access to fresh, safe, and diverse food at the household level. One of their most important contributions is improving dietary diversity, as a well-planned kitchen garden can include a variety of vegetables, fruits, leafy greens, legumes, and herbs that supply essential nutrients such as vitamins (A, C, and B-complex), minerals (iron, calcium, zinc), proteins, and dietary fiber. Regular consumption of these freshly harvested foods helps prevent malnutrition, micronutrient deficiencies, and lifestyle-related diseases. Since produce is consumed soon after harvest, nutrient losses are minimal compared to market-bought foods, thereby enhancing the nutritional value of meals.

An average person requires about 300 g of vegetables and nearly 100 g of fresh fruits per day, which includes around 50 g of green leafy vegetables, 200 g of other vegetables, and 50 g of roots and tubers. According to ICMR recommendations, pregnant women should consume at least 100 g of leafy vegetables daily; however, their actual intake is often far below this level due to limited availability. Traditionally, many rural households grow vegetables in their backyard for home consumption, yet deficiencies in essential vitamins and minerals still persist. This is largely due to unplanned and unorganized vegetable cultivation, which restricts year-round availability and diversity. Recognizing the critical role of vegetables in daily diets and their inadequate supply, Krishi Vigyan Kendras have undertaken several training programs and demonstrations under the Women in Agriculture discipline to promote improved kitchen gardening practices.

Kitchen or nutritional home gardens are usually established close to the house and are designed to provide a continuous supply of vegetables, fruits, and other food crops throughout the year. These gardens help families save money and time, while also offering a healthy, productive, and eco-friendly activity that involves all family members. In addition, home gardens support the recycling of household waste, especially when compost pits are used to convert organic waste into valuable manure. Growing a wide variety of crops at home is one of the simplest and most effective ways to ensure access to a balanced diet rich in both macro- and micronutrients. At a time when more than half of the global population faces chronic food insecurity and food production is expected to

increase by nearly 70% to meet the dietary needs of the world's population by the 2050s, the emphasis has shifted toward achieving balanced diets that not only meet caloric needs but also enhance health, disease resistance, life expectancy, and overall quality of life.

Kitchen gardens also strengthen food and nutritional security by reducing household dependence on external food markets, especially during price fluctuations, supply disruptions, or seasonal shortages. They provide an affordable source of nutritious food, making them particularly beneficial for low- and middle-income families. By growing vegetables at home, households can allocate saved income toward other essential needs such as healthcare and education. They serve as practical learning spaces where children and adults gain knowledge about food sources, and balanced diets. In addition, kitchen gardens encourage the use of safe and sustainable cultivation practices, including organic manures, composting of kitchen waste, and minimal use of chemical pesticides, which improves food safety and environmental health. Beyond direct nutritional benefits, kitchen gardens promote nutrition awareness and healthy eating habits among family members. It also supports women's empowerment, as women often manage these gardens, giving them greater control over household nutrition and food choices.

State-level initiatives taken to promote kitchen or nutritional gardens

State-level initiatives in India demonstrate a growing focus on nutritional gardens and kitchen gardens as tools for nutritional security. These programs help households and institutions produce fresh, diverse, and nutrient-rich foods locally, reduce dependence on markets, improve dietary diversity, and link agricultural practices with nutrition outcomes. The models vary across states from backyard gardens and school gardens to Anganwadi food production often converging with rural employment schemes and agricultural extension services. Here are some important state-level initiatives by various Indian governments to promote kitchen or nutritional gardens and support nutritional security.

1. Odisha nutrition gardens under odisha livelihoods mission

Odisha Govt., in collaboration with other partners, has established large numbers of nutrition gardens across villages to enhance household nutrition and income. Initially rolled out in selected districts, the program was scaled up to cover hundreds of thousands of homes by investing significantly and working with schemes like MGNREGS. These gardens focus on growing vegetables that are both consumed at home and sold for income, helping tackle malnutrition and food insecurity at the ground level.

2. Cluster nutritional kitchen garden scheme (Arunachal Pradesh)

The Government of Arunachal Pradesh has introduced the Cluster Nutritional Kitchen Garden Scheme to encourage households, including marginal farmers, to develop kitchen gardens. This scheme aims to improve self-sufficiency in vegetables and nutrition, reduce dependence on external sources for produce, and generate income from surplus yields. Local officials such as MLAs and Deputy Commissioners support implementation at the district level to ensure effective community participation.

3. Karnataka – 'Akshara Kaitoota' kitchen gardens in schools

The Karnataka Horticulture Department, in collaboration with MNREGA, has developed kitchen gardens known as Akshara Kaitoota in government schools. These gardens aim to promote consumption of fresh vegetables and fruits among school children and integrate nutrition into the school environment. Key approaches of this programme were use of school

land to grow nutrient-rich produce and integration with horticultural and rural development planning..

4. Kudumbashree agri nutri garden project

The Kudumbashree Mission launched the Agri Nutri Garden project to establish organic nutritional gardens at the household level across Kerala. The goal is to increase availability of nutritious vegetables and fruits for families to grow at home, promote self-sufficiency in vegetable production, and improve nutritional outcomes. Under this initiative, beneficiaries receive seeds, training, and guidance to cultivate at least five vegetable varieties and two fruit trees in their own homesteads.

5. Promotion of household nutrition gardens under agriculture department

The Department of Agriculture & Farmer's Welfare (DAFW) in Kerala has included promotion of homestead nutrition gardens as part of its Poshaka Samrudhi Mission, aiming to encourage households to maintain a permanent nutrition garden with seasonal and perennial vegetables, spices, and tubers. Financial support is provided (e.g., Rs 500 assistance per garden), along with seedlings and organic inputs to strengthen food and nutrition security. The program targets one lakh homesteads initially and is being piloted in several panchayats.

6. Nutrition garden mobile unit in Attappady

Under the Attappady Comprehensive Tribal Development Project, Nutrition Garden Mobile Units were launched in tribal hamlets of Palakkad district to grow organic vegetables, pulses, and tubers that supply community kitchens and improve local nutritional status. So far 32 such units have been established, with plans for expansion.

Conclusion

Kitchen gardens play a vital role in ensuring nutritional security by providing households with regular access to fresh, diverse, and nutrient-rich foods. They directly address hidden hunger and micronutrient deficiencies by encouraging the consumption of vegetables, fruits, and leafy greens essential for a balanced diet. Beyond improving dietary diversity, kitchen gardens reduce dependence on market supply, lower food expenses, and minimize nutrient losses associated with storage and transportation. They also promote food safety through the use of organic inputs and environmentally sustainable practices such as composting and efficient water use.

At a broader level, kitchen gardens contribute to community resilience, nutrition awareness, and women's empowerment, while strengthening local food systems and biodiversity conservation. Government-led initiatives at national and state levels, along with support from institutions like Krishi Vigyan Kendras and self-help groups, have further highlighted their importance in addressing food and nutrition challenges, particularly among vulnerable populations. In the context of rising food insecurity, population growth, and changing dietary patterns, kitchen gardens emerge as a simple, cost-effective, and sustainable strategy to enhance household nutritional security, improve public health, and support long-term sustainable development.

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DIRECT SEEDED RICE UNDER CHANGING CLIMATE: CONSTRAINTS, ADVANTAGES AND SUSTAINABLE YIELD ENHANCEMENT APPROACHES

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Introduction

Rice (*Oryza sativa*) is one of India's most important staple food crops, particularly in the North-West Indo-Gangetic Plains (IGPs), where rice and wheat production are critical for national food security. The traditional puddled transplanting system faces significant challenges due to depleting water resources, labor shortages, and rising green house gas emission (Singh *et al.*, 2024). These factors necessitate a shift towards more sustainable rice cultivation practices, such as Direct-Seeded Rice (DSR). DSR involves sowing seeds directly into the main field without transplanting from a nursery. It can be done through wet seeding (sowing pre-germinated seeds in puddled soil), water seeding (sowing in standing water), or dry seeding (sowing in a prepared seedbed). This method is gaining popularity due to its potential to improve water efficiency and environmental sustainability (Chaudhary *et al.*, 2023). However, DSR comes with several challenges, including weed infestation, pest and disease attacks, poor crop establishment, water management issues, soil health degradation, lodging, and stagnant yields. To overcome these problems, improved agronomic practices, effective weed and pest control strategies, and the selection of suitable rice varieties are essential. Understanding these challenges is crucial to maximizing the benefits of DSR while ensuring productivity and sustainability.

Why DSR?

1. **Water Scarcity:** Agriculture water use is projected to rise by 20% by 2025, with irrigation accounting for 70% of total global water withdrawals. Conventional rice cultivation requires a significant amount of water—up to 5,000 liters to produce 1 kg of rice. DSR has the potential to save water compared to PTR, as it requires less irrigation and is more tolerant of water stress. This makes DSR a more climate-resilient practice.
2. **Labor Shortage:** DSR significantly reduces labor requirements by eliminating the need for raising nurseries, uprooting seedlings, puddling, and transplanting. Traditional transplanting requires 25–50 person-days per hectare, whereas DSR requires only about 5 person-days per hectare. The labor demand in DSR is spread over a longer period which reduces reliance on hired labor during peak seasons.
3. **Soil Health:** Puddling in conventional rice cultivation negatively impacts soil health by breaking soil aggregates, destroying capillary pores, dispersing fine clay particles, and forming a hard pan at shallow depths. DSR, especially dry-seeded rice on plowed soil (without puddling), helps maintain soil structure and improves long-term soil health.
4. **GHG Emission:** PTR contributes 10–20% of global methane emissions due to continuous submergence, which creates anaerobic conditions. In contrast, DSR fields are not continuously flooded, reducing methane emissions and making it a more environmentally sustainable rice production method.

5. **Crop Intensification:** Beyond water and labor savings, DSR offers economic benefits by allowing an additional crop to be integrated into the farming system. DSR matures 7–11 days earlier than PTR, creating opportunities for multi-cropping and enhancing overall farm productivity. Its compatibility with different cropping systems has led to its rapid adoption in various regions.

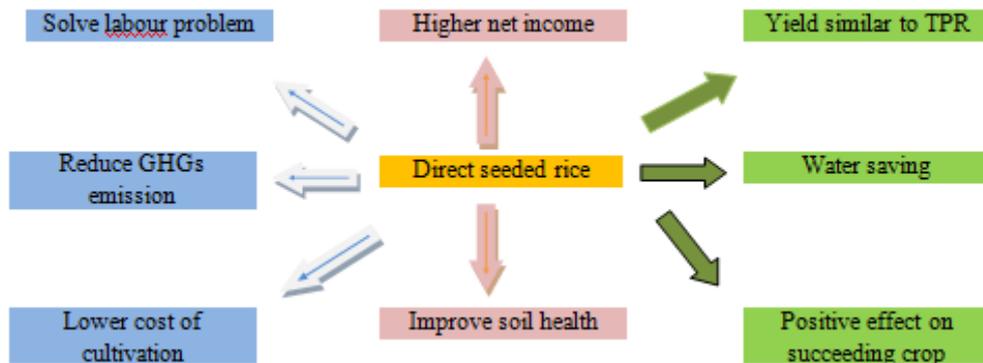


Fig. 1 Advantages of direct seeded rice (DSR) over puddled transplanted rice (PTR)

Constraints associated with DSR

- Weeds:** Weeds are the most significant constraint to the success of DSR. Research indicates that weeds can cause 20–85% yield loss in DSR. The shifting in weed flora is also reported in converting from conventional transplanting (CT-PTR) to DSR.
- Development of herbicide resistance:** Large-scale direct seeding has led to increased herbicide use for weed control. Over reliance on herbicide tends to development of herbicide resistance in certain weed species.
- Emergence of weedy rice:** Weedy rice, also known as red rice (*Oryza sativa* F. *spontanea*), has become a major concern in areas where Dry-DSR has widely replaced CT-PTR. It impaired the milling quality of rice.
- Increase in insect-pest incidence:** The shift from PTR to DSR increases susceptibility to insect pests and diseases. Root-knot nematodes, rice blast, sheath blight becomes more damaging under water stress conditions.
- Lodging:** Lodging, the permanent displacement of the crop stem, is more prevalent in DSR compared to PTR. It makes harvesting difficult and also reduces yield and impairs the quality of rice.

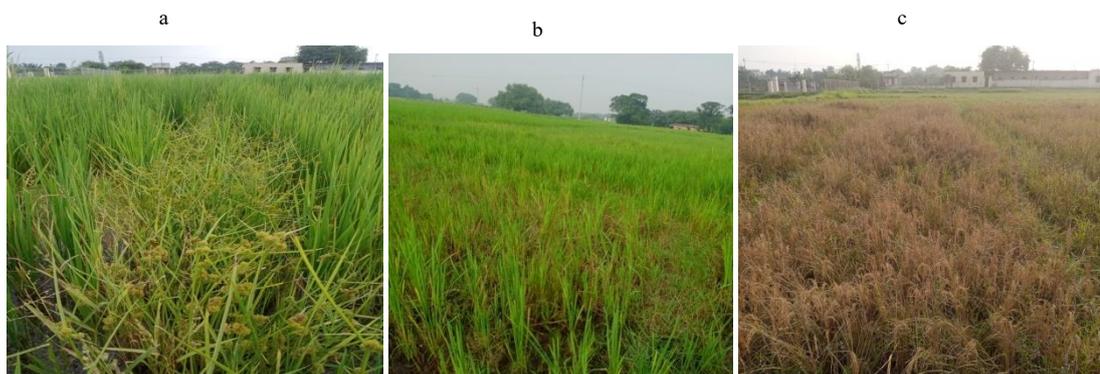


Fig.2 Constraints with DSR; (a) Weed association, (b) uneven crop establishment, (c) crop lodging in DSR

6. **Stagnant yield:** Yield decline has been observed in DSR systems. It may be due to factors such as soil sickness, plant autotoxicity, and continuous DSR cultivation for more than two years.
7. **Nutrient deficiency:** Micronutrient deficiencies are a major issue in DSR. The transition from PTR to DSR affects zinc (Zn) and iron (Fe) availability.

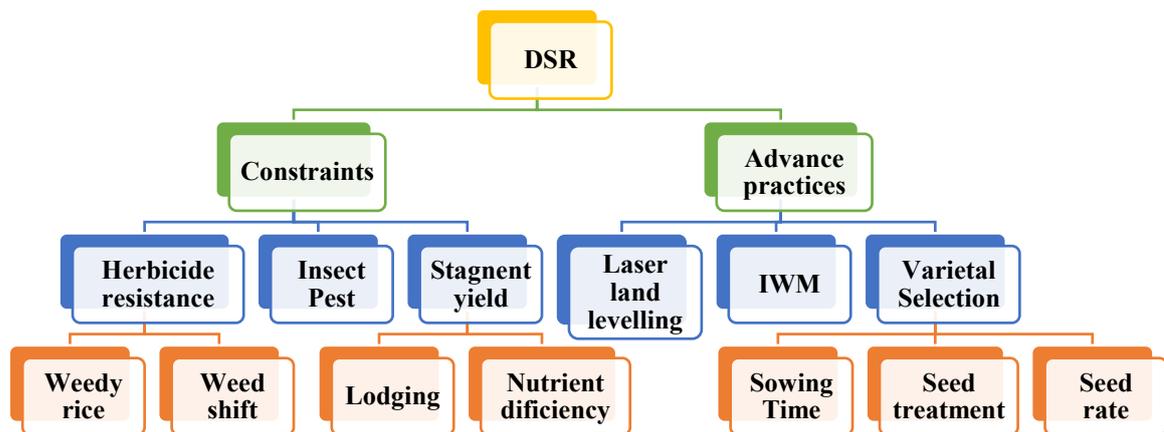


Fig. 3 Constraints and possible solutions for enhancing yield of DSR

Smart Package and practices for enhancing yield of DSR

1. **Land Preparation:** Laser land leveler should be used to level land at least one month before sowing of rice. Precision leveling increased cultivable area by 3-6% by removing numerous field bunds and irrigation channels. Minimum tillage or zero-tillage along with DSR can be used to lowers the production cost (Sandhu *et al.*, 2021).
2. **Optimum sowing time:** The best planting time for DSR is 10-15 days before the onset of the monsoon. Usually mansoon arrived in Eastern Uttar Pradesh near 20-25 June, the ideal seeding time in this region is approximately June 15-20.
3. **Selection of variety:** In general, high yielding, short duration and drought-tolerant varieties are most suitable for DSR. Varieties like NDR-359, Shabhazi dhan (For drought-prone environments), BPT-5204, MTU- 7029, Moti, Swarna-Sub1 (water logging conditions), Arize 6444, etc. are most suited for Eastern Utter Pradesh.

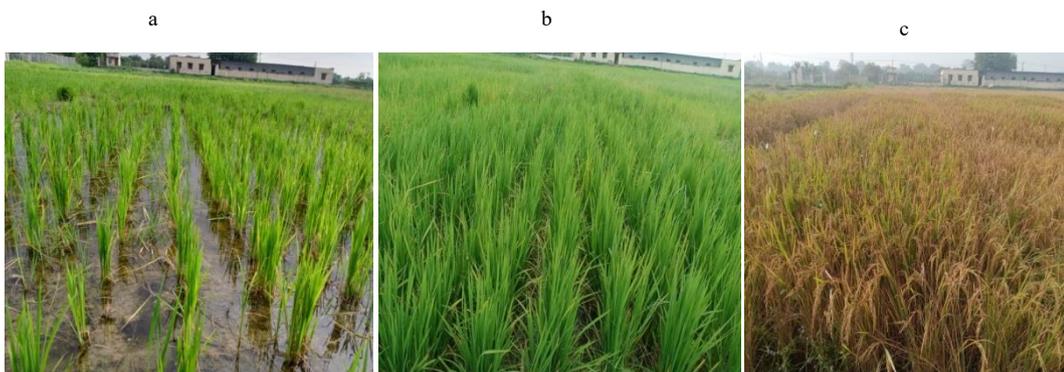


Fig. 4 Smart practices in DSR; (a) crop establishment, (b) weed management, (c) harvesting stage of DSR

4. **Seed treatment:** Seed priming technique helps to improve emergence as well as crop establishment of DSR. Various treatments included hydropriming (Immersing seeds in water), chemical treatment (using potassium nitrate, gibberellic acid etc.), nanoprimering (using nanoparticles like zinc oxide nanoparticles) can be used. For management of soil borne pathogen, fungicide (10 g bavistin + 1g streptocyclin in 10 litre water solution for 10 kg seed) can be used.
5. **Seed rate and sowing depth:** A seed rate of 6-8 kg/acre has been found optimum for DSR. Sowing depth for dry DSR is 2-3 cm and for wet DSR 3-5 cm is optimum. The row to row spacing should be 20 cm.
6. **Nutrient Management:** The recommended doses of P, K and Zinc for DSR and PTR are same and apply as basal dose. N @ 150 kg /ha should be applied in three splits. In case of basmati rice, 25% higher N dose is applied. For iron deficiency, ferrous sulphate @0.5% solution should be applied. .
7. **Weed management:** Weeds are the major constraint in DSR, so effective weed management is critical (Shekhawat *et al.*, 2020).
8. **Irrigation management:** A light irrigation should be applied after sowing in dry DSR, for proper seed germination. Water should not stagnate for long time at time of germination. In Wet DSR, a light irrigation should be applied after full germination to maintain proper soil moisture. Irrigation should be applied at an interval of 5 to 6 days (depending on weather conditions) after crop establishment.

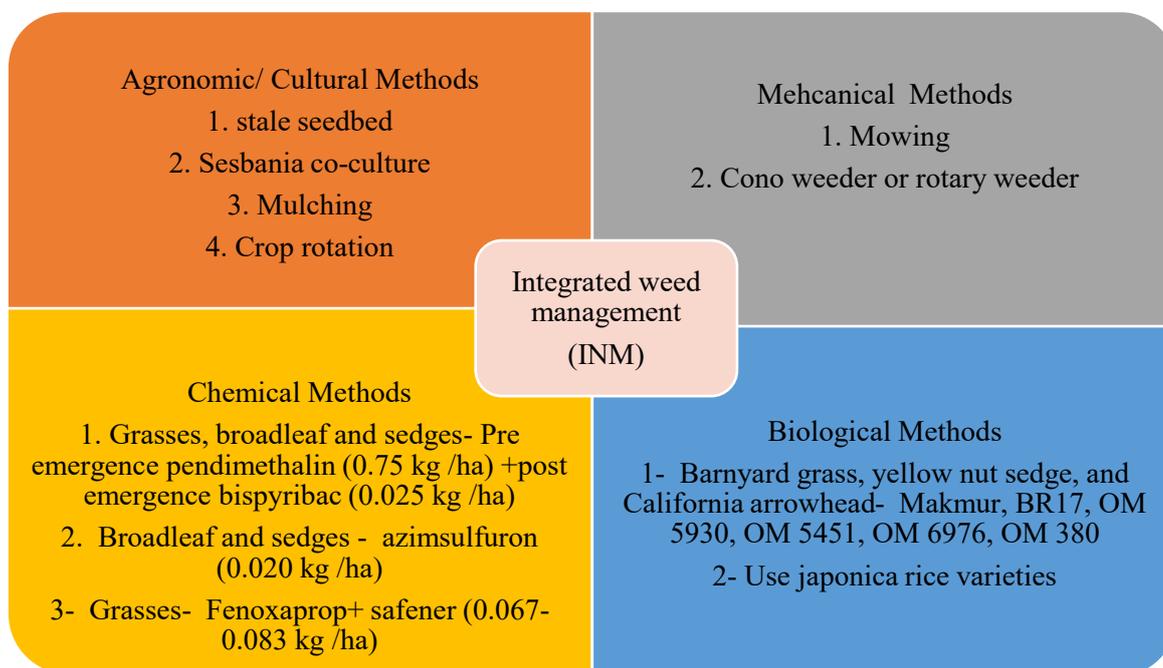


Fig. 5 Integrated weed management strategies in direct seeded rice (DSR)

Conclusion

A sustainable and climate-resilient substitute for conventional transplanted rice (TPR) is Direct Seeded Rice (DSR). It is a viable option for areas with limited resources because of its benefits, which include decreased greenhouse gas emissions, less labor and water needs, and financial gains. However, integrated management solutions are required to address issues such crop lodging,

herbicide resistance, weed control, and the occurrence of pests and diseases. DSR may greatly increase rice production while preserving natural resources by using efficient weed-control strategies, optimizing agronomic techniques, and selecting appropriate cultivars. As resource constraint and climate change keep threatening agricultural sustainability, DSR shows promise as a low-impact method of maintaining food security.

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PREVENTING LIVESTOCK DISEASES THROUGH PROPER HOUSING, SANITATION, AND BIOSECURITY

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Abstract

Livestock productivity and health are greatly influenced by housing conditions, sanitation, and disease control practices followed on the farm. Poor shed design, unhygienic surroundings, and lack of biosecurity often lead to frequent disease outbreaks, economic losses, and reduced animal performance. Proper site selection, well-ventilated housing, regular cleaning and disinfection, quarantine of newly purchased animals, balanced nutrition, vaccination, and effective waste disposal play a vital role in preventing infectious diseases. Simple management practices such as pest control, foot baths, and record keeping further strengthen farm biosecurity. Adoption of these low-cost and practical measures can significantly improve animal health, enhance productivity, and ensure sustainable livestock farming. This article highlights farmer-friendly approaches to housing, sanitation, and disease prevention for different classes of livestock.

Introduction

Livestock health and productivity depend not only on feed and breed, but also on housing, disease control, and sanitation. Many disease outbreaks in farms occur due to poor shed design, unhygienic surroundings, and lack of biosecurity measures. Simple improvements in housing and cleanliness can significantly reduce losses and improve farm income.

Importance of Proper Livestock Housing

Good housing protects animals from extreme weather, reduces stress, and helps them express their full genetic potential for growth, milk, meat, or reproduction. A well-designed shed also plays a crucial role in preventing disease spread.

Key Points in Site Selection

- Farms should be located away from other livestock farms, markets, slaughterhouses, water bodies, and feed mills
- The land should be elevated, with good drainage to avoid water stagnation
- Proper orientation of sheds helps keep floors dry:
 - East–West orientation is suitable in very hot areas (above 30 °C)

Fencing the farm, wheel dips at the entrance, hand-wash facilities, and restricted entry of visitors improve structural biosecurity.

Design Features that Reduce Disease

- Good cross-ventilation and ridge ventilation
- Washable floors and walls with proper slope
- Adequate space between sheds (at least twice the shed width)

- Separate quarantine and isolation sheds
- Proper waste and carcass disposal systems

Dry, well-ventilated sheds reduce humidity, which otherwise predisposes animals—especially young stock—to respiratory diseases.

Disease Control Measures in Livestock Farms

Disease prevention is always cheaper than treatment. The following practices are essential:

1. Quarantine and Isolation

- Newly purchased animals should be quarantined for at least 40 days
- Sick animals must be immediately isolated
- Separate feeding and watering facilities for sick animals

2. Selection of Healthy Animals

- Purchase animals only from known and disease-free sources
- Check vaccination and health history before introduction

3. Nutrition and Immunity

Balanced nutrition strengthens immunity. Deficiencies of vitamins and minerals reduce disease resistance and increase susceptibility to infections.

4. Deworming and Vaccination

- Young animals: monthly deworming
- Adult animals: twice a year (before and during monsoon)
- Follow regular vaccination schedules
- Ring vaccination should be done during outbreaks

Sanitation: The Foundation of Disease Prevention

Sanitation involves cleaning + disinfection.

- Daily removal of dung, urine, and waste
- Regular washing of floors, mangers, and water troughs
- Sunlight acts as a natural disinfectant
- During disease outbreaks, thorough disinfection is essential

Organic matter must be removed before applying disinfectants, as it reduces their effectiveness.

Control of Pests and Parasites

Flies, mosquitoes, ticks, rodents, and other pests act as disease carriers.

Preventive steps include:

- Regular cleaning of sheds
- Sealing cracks and crevices
- Removing bushes and stagnant water
- Periodic insecticide spraying
- Rodent control using traps and safe poisons

Safe Disposal of Waste and Carcasses

Animal waste and carcasses can spread serious diseases such as Foot and Mouth Disease, Anthrax, and Salmonellosis.

- Never dispose carcasses near water sources
- Use deep burial or burning
- Prompt disposal prevents spread through insects and rodents

Foot Baths and Spray Races

Foot baths at farm entrances reduce the entry of infectious agents. Spray races help control external parasites and reduce microbial load on animals.

Role of Training and Record Keeping

Educated farm workers are the first line of defence against disease.

- Maintain records of vaccination, deworming, treatments, and visitors
- Train workers on hygiene and zoonotic disease prevention

Conclusion

Healthy livestock begin with clean housing, good sanitation, and strict disease control practices. Even small improvements—like better drainage, regular cleaning, quarantine of new animals, and pest control—can drastically reduce disease incidence and improve farm profitability. Investing in housing and sanitation is an investment in the long-term success of livestock farming.

ENDOPHYTES: THE HIDDEN HELPERS INSIDE PLANTS

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Abstract

Endophytes are microorganisms that reside within plant tissues without causing disease. These hidden inhabitants play a crucial role in enhancing plant growth, improving stress tolerance, and protecting crops from pathogens. In recent years, endophytes have gained attention as eco-friendly alternatives to chemical fertilizers and pesticides. Their ability to improve nutrient acquisition, regulate plant hormones, and enhance resistance against biotic and abiotic stresses makes them promising tools for sustainable agriculture. This review discusses the diversity, mechanisms, applications, and future prospects of endophytic microorganisms in modern crop production systems.

Introduction

Modern agriculture faces major challenges including soil degradation, climate change, excessive use of agrochemicals, and declining crop productivity. To overcome these issues, sustainable and environmentally friendly approaches are urgently needed. Among various biological alternatives, endophytes have emerged as important contributors to plant health and productivity.

Endophytes are bacteria and fungi that colonize internal plant tissues such as roots, stems, leaves, and seeds without causing visible harm. Unlike rhizospheric microorganisms that live in soil around roots, endophytes establish intimate associations within the plant body. This close relationship allows them to directly influence plant metabolism, growth, and defense mechanisms.

With advancements in molecular biology and microbiome research, scientists have begun to recognize the immense potential of endophytes in agriculture. These microorganisms act as “hidden helpers” that silently support plant development and resilience.

Diversity and Classification of Endophytes

Endophytes are widely distributed in nature and are found in almost all plant species, including crops, trees, grasses, and medicinal plants. They exhibit remarkable diversity in terms of taxonomy, physiology, and ecological functions.

Bacterial Endophytes

Common bacterial endophytes belong to genera such as:

- *Bacillus*
- *Pseudomonas*
- *Azospirillum*
- *Enterobacter*
- *Rhizobium*
- *Burkholderia*

These bacteria are mainly involved in nitrogen fixation, phosphate solubilization, hormone production, and disease suppression.

Fungal Endophytes

Fungal endophytes are predominantly represented by:

- *Trichoderma*
- *Fusarium* (non-pathogenic strains)
- *Cladosporium*
- *Penicillium*
- *Aspergillus*

Fungal endophytes often enhance stress tolerance and produce bioactive compounds that protect plants from pathogens and insects.

Modes of Transmission

Endophytes enter plants through:

- Root hairs and lateral roots
- Natural openings (stomata, lenticels)
- Wounds
- Seed transmission (vertical transfer)

They may be horizontally transferred from soil or vertically inherited from parent plants.

Mechanisms of Plant–Endophyte Interaction

The beneficial effects of endophytes arise from complex biochemical and molecular interactions between plants and microbes.

Plant Growth Promotion

Endophytes stimulate plant growth through:

a) Phytohormone Production

Many endophytes synthesize plant hormones such as:

- Indole-3-acetic acid (IAA)
- Gibberellins
- Cytokinins
- Abscisic acid

These hormones regulate root development, shoot growth, and flowering.

b) Nutrient Mobilization

Endophytes enhance nutrient availability by:

- Fixing atmospheric nitrogen
- Solubilizing phosphate and potassium
- Producing siderophores for iron uptake

This improves nutrient use efficiency and reduces fertilizer dependency.

Biotic Stress Resistance

Endophytes protect plants from diseases and pests through:

- Production of antibiotics and antifungal compounds
- Competition for nutrients and space
- Induction of systemic resistance (ISR)
- Secretion of lytic enzymes (chitinase, glucanase)

These mechanisms suppress pathogenic microorganisms and insect pests.

Abiotic Stress Tolerance

Endophytes help plants survive under adverse environmental conditions such as:

- Drought
- Salinity
- Heavy metal toxicity
- Temperature extremes

They achieve this by regulating osmolytes, antioxidants, stress-responsive genes, and ion transport systems.

Modulation of Plant Defense Pathways

Endophytes activate signaling pathways involving:

- Salicylic acid
- Jasmonic acid
- Ethylene

These pathways enhance the plant's innate immune system and prepare it for future stress exposure.

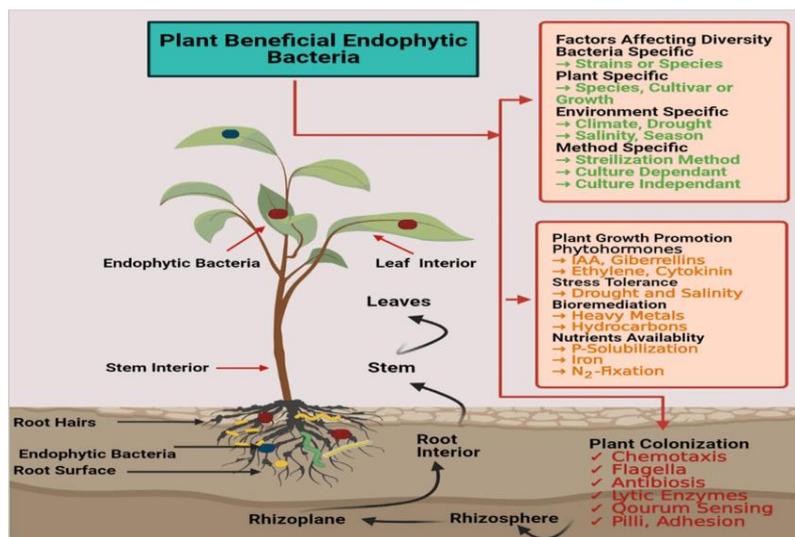


Fig:1 Endophyte colonization and interaction with plants

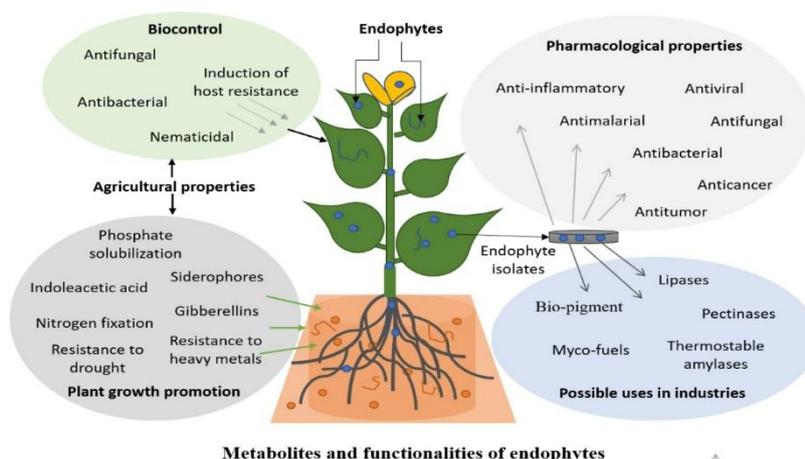


Fig:2 Endophytes produce compounds that enhance plant health and resistance

Agricultural Applications of Endophytes

Endophytes have immense potential in developing sustainable agricultural practices.

Endophyte-Based Biofertilizers

Endophytic biofertilizers improve nutrient uptake and plant growth. Examples include:

- Nitrogen-fixing *Azospirillum* in cereals
- Phosphate-solubilizing *Bacillus* in legumes
- Endophytic *Rhizobium* in non-leguminous crops

These bioinoculants reduce chemical fertilizer usage.

Biocontrol Agents

Several endophytes act as biological control agents:

- *Trichoderma* against soil-borne fungi
- *Bacillus subtilis* against bacterial wilt
- *Pseudomonas fluorescens* against fungal pathogens

They provide long-term disease protection from inside plant tissues.

Stress Management in Crops

Endophytes are used to improve crop performance under stress conditions:

- Drought-tolerant endophytes in wheat and maize
- Salt-tolerant bacteria in rice and cotton
- Heavy metal-resistant strains in phytoremediation

These applications are crucial for climate-resilient agriculture.

Enhancement of Secondary Metabolites

In medicinal plants, endophytes enhance the production of valuable compounds such as:

- Alkaloids
- Flavonoids
- Terpenoids
- Phenolics

This has applications in pharmaceutical and nutraceutical industries.

Seed and Tissue Culture Applications

Endophytes are incorporated into:

- Seed coating technologies
- Micropropagation systems
- Plant tissue cultures

This ensures early colonization and uniform benefits.

Isolation and Characterization of Endophytes

Isolation Techniques

Common steps include:

1. Surface sterilization of plant tissues
2. Tissue maceration
3. Serial dilution
4. Culturing on selective media
5. Purification of isolates

Molecular Identification

Modern techniques include:

- 16S rRNA gene sequencing (bacteria)
- ITS sequencing (fungi)
- Metagenomic analysis
- Next-generation sequencing (NGS)

These tools help identify unculturable endophytes and analyze community structure.

Functional Characterization

Endophytes are screened for:

- IAA production
- Phosphate solubilization
- Siderophore production
- Antagonistic activity
- Stress tolerance

This determines their agricultural potential.

Challenges and Limitations

Despite promising potential, several challenges remain:

- Inconsistent field performance
- Host specificity
- Survival under field conditions
- Regulatory issues
- Limited commercialization

Environmental factors, soil type, crop variety, and management practices strongly influence endophyte efficacy.

Future Prospects

The future of endophyte research is highly promising with emerging technologies.

Genomic Engineering

CRISPR and synthetic biology may be used to:

- Improve beneficial traits
- Enhance colonization ability
- Increase stress tolerance

Microbiome Engineering

Designing customized endophytic consortia for specific crops and regions will be a major breakthrough.

Integration with Digital Agriculture

AI reminder systems and precision farming tools can help optimize endophyte application timing and dosage.

Policy and Commercialization

Supportive government policies and industry participation will accelerate large-scale adoption.

Conclusion

Endophytes represent a hidden but powerful resource for sustainable agriculture. Their ability to promote growth, protect against diseases, and enhance stress tolerance makes them valuable allies

for farmers and researchers. With advances in molecular biology, microbiome research, and biotechnology, endophyte-based solutions are expected to play a central role in future farming systems. Integrating endophytes into crop management practices can reduce chemical inputs, improve soil health, and contribute to global food security.

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CLIMATE CHANGE AND INSECT PESTS: WHY INSECTS ARE SHIFTING THEIR GEOGRAPHY IN A WARMING WORLD

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Abstract

Climate change is now increasingly acknowledged as a major driver that influences the occurrence, distribution, and effects of insect pests on a global scale. Changes in temperature patterns, atmospheric concentration of CO₂, precipitation, and extreme weather events have a direct influence on the physiology, survival, reproduction, and migration of insects. Insects, being poikilotherms, show a rapid response to even slight changes in climate, resulting in the expansion of their geographical distribution, increased survival during overwintering, increased voltinism, and the development of invasive and secondary pests as serious threats. This review article summarizes the present understanding of the role of climate change in the migration and population dynamics of insect pests, with special reference to the Indian agricultural scenario.

Keywords : Climate change; insect pests; geographic shift; pest dynamics; invasive species; voltinism; agro-climatic zones; pest management; food security

Introduction

Climate change has a profound impact on agricultural production by changing the climatic determinants of temperature, atmospheric CO₂ concentration, and precipitation regimes. These, in turn, affect food security and crop plant physiology, which indirectly influences crop pests. Insects, being poikilothermic organisms, are among the most conspicuous responders to such changes, resulting in expanded geographic distributions, improved overwinter survival, additional generations, and enhanced risks due to invasive pests and insect-borne diseases. The projected loss in India's crop production by 2100 CE is estimated at 10–40%, despite potential growth-promoting effects of elevated CO₂ on crop growth. The dynamics of pests and diseases is expected to be significantly altered. A common driver behind these changes is increased temperatures, erratic rainfall, and mild winters, which subtly reshape the biology and behavior of insects, thus allowing pests to expand their range and enhance the intensity of attack on crops. Insects' growth, reproduction, survival, and dispersal are all directly regulated by environmental temperature and humidity; even minor changes in the climate can trigger considerable biological responses. These dynamics pose economic risks to crops and require adaptive management approaches to meet evolving pest pressures. The present article analyses how local climatic variables affect pest species and enumerates future research priorities.

Why are insects moving?

Traditionally, insect pests have been restricted by cold winters, unfavorable humidity, or lack of host crops. Climate change is weakening many of these natural barriers. Areas previously too cold-northern plains, high elevations, or temperate regions-become favourable for insect survival. As a

result, pests move northward, southward, or to higher elevations. Higher temperatures shorten the life cycles of insects; a pest that formerly completed two generations per season may now realize three or four. This hastens population buildup, increases the risk of development of resistance, and heightens crop losses. Cold winters previously served as a natural restraint by reducing the number of overwintering eggs, larvae, or pupae; due to shorter, warmer winters, more insects survive to infest crops during the next season. Milder winters under global warming conditions improve overwintering success rates for many pests. For example, *Helicoverpa zea* (cotton bollworm) and *Ostrinia nubilalis* (European corn borer) show better overwintering success in warmer latitudes and hence give rise to early-season epidemics. Increased survival similarly extends voltinism, *i.e.*, the number of generations annually produced (Sorahia *et al.*, 2025).

Indian farming is under pressure:

India's many agro-climatic zones render it especially weak to pests that move because of climate change. Some tendencies that have been seen are:

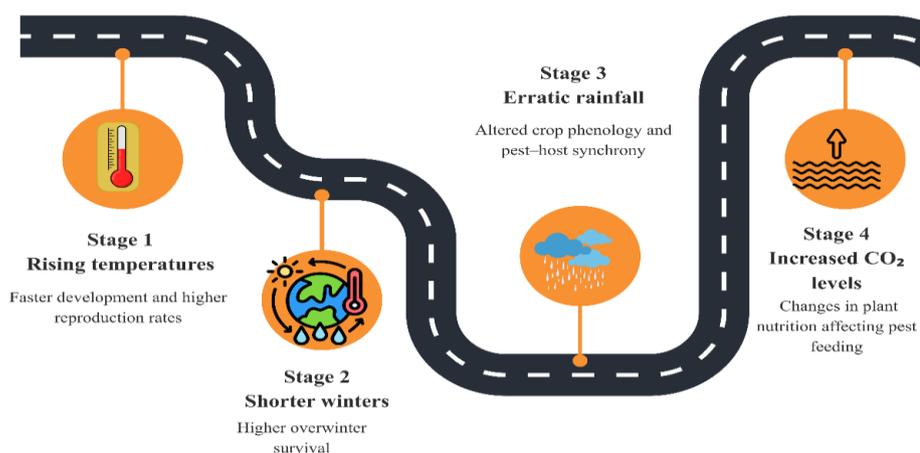
- Infestations at the start of the season, before farmers are ready
- Pest activity that goes on for a long time after normal crop phases
- Secondary pests becoming main pests
- More pests in areas that get their water from rain

Climate change is also affecting vector insects, which is making viral and phytoplasma illnesses spread more quickly in crops.

Climate change

Farmers in India are reporting more and more insect pests that they didn't see before or that they had never seen before. Pests are attacking crops earlier in the season, and the pressure from pests lasts longer than usual. Traditional ways of getting rid of pests are often not enough.

Key climate factors affecting insect pests include:



These things are changing the natural rules that used to keep insects to certain areas. Higher temperatures affect several areas of insect biology, like how they move and how quickly they break down food. This causes changes in pest populations and dynamics. The forecast of insect pest prevalence under climate change scenarios suggested that *Spodoptera litura* on groundnut and *Helicoverpa armigera* on pigeonpea are anticipated to produce two to three additional generations during remote and very remote future climate change periods, attributed to rising temperatures

across most regions of India (Rao *et al.*, 2022). For instance, warming and drought conditions have led to more bark beetle outbreaks in forests, which have killed a lot of trees (Mehla *et al.*, 2026). When its warmer, insects live shorter lifetimes, which means there are more of them. This is especially true in temperate places where insects do well in the summer. Scientists think that geographic ranges will move towards the poles or higher places, along with new trends in pest populations, including greater herbivory. However, in tropical regions with temperatures nearly optimal for pests, growth rates may decelerate. Laboratory data suggest that crops like wheat and rice would face varying insect population dynamics under future environmental conditions, exacerbating hazards to agricultural yields. Higher levels of CO₂ in the air can also influence the number and behaviour of insect pests by modifying how they devour plants that they live on. This effect varies across C₃ and C₄ plants. Higher levels of CO₂ can also change how plants make secondary metabolites, such as defence chemicals like phenolics, tannins, and terpenoids (Mehla *et al.*, 2026). Changes in rainfall patterns also affect how often pests come up, but more severe weather can have different effects on various types of pests. For instance, some pests might die in heavy rain, while others can live in dry weather. Extreme rainfall events, which are typically caused by changes in oceanic oscillations that are caused by climate change, make perfect breeding circumstances for locusts (such the Desert Locust and the African Migratory Locust). These insect swarms have the potential to cause extensive crop losses across large geographic areas. Climate change may drive invasive insect species to migrate into new regions, with adverse implications for agricultural production. Prior studies conducted in India point to associations between climate change, increasing insect populations, and the incidence of disease outbreaks. Additionally, climate change is also disruptive to insect pollinators, thus reducing their abilities to carry out effective pollination of crops and threatening long-term food security and biodiversity. Another critical aspect of the impact of climate change involves agrochemical use, given that temperature affects pesticide efficacy and degradation rates, which requires changes to practices of application. Changes to environmental conditions affect trophic interactions of pests and their natural enemies and complicate biological control applications. To mitigate uncertainties brought about by climate change, it is necessary to develop robust pest management strategies that integrate traditional and contemporary technologies to enhance the resilience of agricultural systems. (Singh, 2023; Panigrahi *et al.*, 2025).

Climate change doesn't just effect bugs; it changes the whole ecosystem of crops.

- Higher levels of CO₂ can lower the nitrogen content in plants, which makes insects eat more aggressively.
- Plants that are stressed are more likely to be attacked by pests.
- Changing the timings of flowering and cropping affects the populations of natural enemies.

This imbalance generally favours pests over predators and parasitoids, which makes nature's natural pest control system less effective.

Table 1. Major insect pests reported in India under changing climate, with endemic/epidemic occurrence

Pest	Scientific name	Major host crops	Region	Endemic / epidemic status	Climate / weather link	References
Sugarcane woolly aphid	<i>Ceratovacuna lanigera</i>	Sugarcane	Maharashtra, Karnataka	Shift from minor to epidemic pest with 30% yield loss in outbreaks	Abnormal weather, warm humid conditions favoured rapid population build-up	Mukhtar <i>et al.</i> , 2023
Brown planthopper (BPH)	<i>Nilaparvata lugens</i>	Rice	Kerala; North India (Punjab, Haryana, U.P., Delhi)	Recurrent epidemics; crop failure on >3.3 lakh ha in 2008–09	High temperature, high humidity, elevated CO ₂ increase fecundity and outbreaks	Prasannakumar <i>et al.</i> , 2012; Singh 2023
Cotton mealybug	<i>Phenacoccus solenopsis</i>	Cotton, many field and horticultural crops	Gujarat, Punjab, Haryana, other cotton belts	Now endemic with periodic severe flare-ups (30–40% loss)	Hot, dry conditions and reduced rainy days favoured spread and persistence	Mukhtar <i>et al.</i> , 2023
Fall armyworm	<i>Spodoptera frugiperda</i>	Maize, sorghum and many others	Karnataka, West Bengal and adjoining states	Recently invasive; local epidemics with up to 58% yield loss	Warm, moderately humid weather and mild winters aid survival and spread	Dhar <i>et al.</i> , 2019; Singh 2023
Thrips	<i>Thrips parvispinus</i>	Chilli, groundnut, cotton, vegetables	Andhra Pradesh and other warm dry zones	New invasive thrips causing epidemic damage in chilli	Hot, dry spells and pesticide misuse plus changing rainfall patterns	Sireesha <i>et al.</i> , 2021; Panigrahi <i>et al.</i> , 2025

Conclusion

Climate change is placing pressure on agricultural systems, and this may limit the ability to meet food production targets in the future. Impacts can be reduced in the short run through adaptation strategies, but building adaptive capacity will be necessary through research, policy reform, and investment. The exact cost of adaptation is not yet known, but it is likely to be high. For example, wheat production might face significant losses from rising temperatures alone. Key actions include breeding climate-tolerant genotypes, providing dependable weather forecasts and risk management services for farmers, offering financial incentives for resource conservation, investing in technologies that use water more efficiently, and making food security a centrepiece of climate

policy. Solution implementation should consider farm-level vulnerabilities, especially in poor countries where climate change is already having an impact.

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HEAT STRESS–INDUCED FLOWER DROP AND PIGMENT DEGRADATION IN FLOWER CROPS

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Abstract

Flower crops are the foundation of an ornamental business worth billions of dollars, but their beautiful flowers are incredibly vulnerable to heat stress, which causes them to drop their flowers in large amounts and suffer irreversible pigment loss during heat waves caused by changes in climate. Supra-optimal temperatures more than 35°C during critical flowering periods disturb physiological homeostasis, increasing ethylene levels, reducing pollen viability, and leading to water deficiencies that cause bud abscission. At the same time, heat negatively affects the stability of anthocyanin and carotenoids through activity of the enzymes and oxidative bursts, resulting in discoloured petals, which reduce their market value. These mutually reinforcing reactions reduce the yields of species such as roses and chrysanthemums by 30-70 percent, which explains why specific interventions are necessary. Losses are effectively controlled through agronomic interventions such as shade, accurate irrigation, nutrient addition, and the choice of cultivar, which is heat-tolerant, hence sustainable floriculture in warming conditions.

Keywords: Heat stress, flower drop, pigment degradation, floriculture, abiotic stress

Introduction

Flower crops are an essential part of world agriculture, which generates a significant portion of the economic incomes due to the ornamental trade, landscaping, and cultural celebrations as well as providing significant aesthetic gratification that improves the well-being of humans. Flower retention and bright coloration are critical to the marketability of such crops since high-quality blooms sell at higher prices and are favored by consumers, and any decrease in the number of blooms or the strength of pigments can be devastating to the commercial viability of the sensitive species such as roses, chrysanthemums, and marigolds (Kumar *et al.*, 2022).

In the intensifying conditions of climate change, heat stress becomes one of the major abiotic challenges, and increased temperatures and extended heat waves interfere with reproductive physiology in floriculture production areas across the globe. When the temperature surpasses 35°C at key flowering periods, physiological disturbances develop and are most noticeable through flower losses and pigment loss, with anthocyanins and carotenoids disintegrating and causing fading color and reduced ornamental value (Jagadish, 2020; Zhang *et al.*, 2023; Yang *et al.*, 2023).

These reactions are related to hormonal imbalances of heating which include increased ethylene and reduced cytokinins, oxidative harming of the reactive oxygen species that disrupts membrane integrity and stability of pigments. With the rising scope of protected cultivation and worsening thermal extremes in open-field systems, a clear need to identify the mechanisms of heat stress in

flower crops will be necessary to develop resistant cultivars and management approaches to protect this lucrative sector (Kumar, Jin, and Teng, 2023).

What is Heat Stress in Flower Crops?

The heat stress on flower crops happens when ambient temperature falls below the physiological limits at which plants can perform optimally, negatively affecting normal growth, development and reproductive functions (Jagadish, 2020). In contrast to normal warm conditions which promote optimum metabolism, heat stress exposes supra-optimal temperatures, usually higher than 30-35°C in most species, which interferes with cell homeostasis and results in adaptive or pathological responses. Figure 1. Theoretical depiction of heat stress impacting flower crops with exposure to supra-optimal temperatures and the subsequent primary physiological abnormalities, such as high canopy temperature, decreased transpiration, diminished photosynthetic performance, and early hypersensitivity of reproductive organs (Yang *et al.*, 2023).

Flower crops also have a limited range of temperature; an example is the roses and carnations, which are more active at daytime 18-25°C and nighttime 15-20°C and the chrysanthemums, which grow best at 20-28 degC. Supra-optimal heat is something that sharply deviates of these optima, increases respiration, stops photosynthesis, and changes the hormone signaling (Zhang *et al.*, 2023).

These crops are particularly susceptible because they grow indeterminately, take long to flower, and invest large quantities of reproductive structures, making them ideal targets of thermal damage. The severity of heat stress depends on the intensity (exceeded the threshold) and the length of the exposure (hours to days of exposure), and even short-term exposures above 40 °C lead to irreversible damage in vulnerable genotypes (Jagadish, 2020).

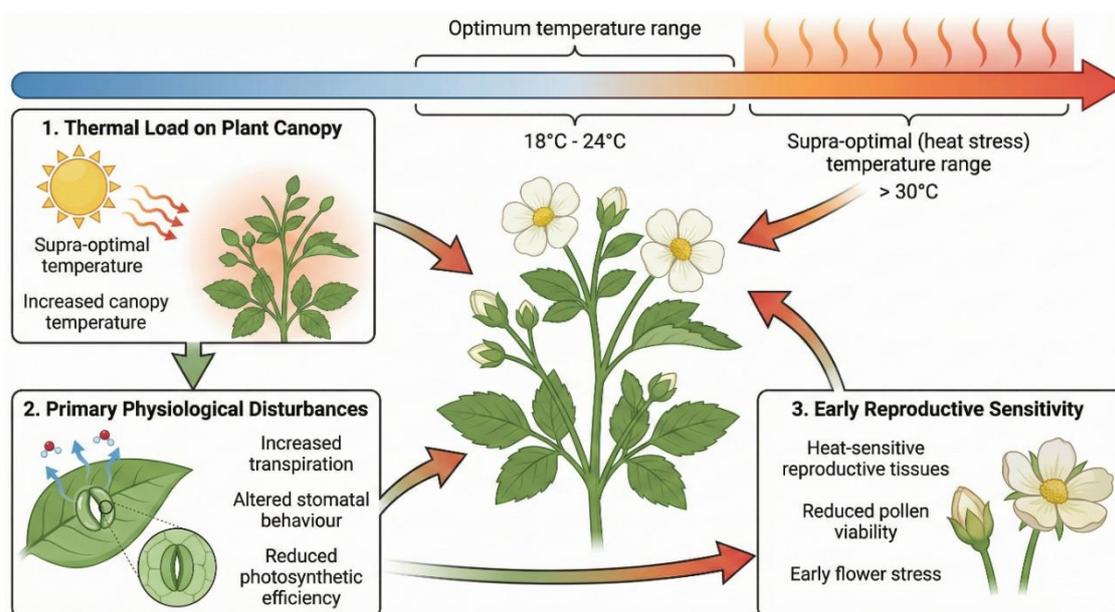


Figure 1. Overview of heat stress in flower crops showing supra-optimal temperature exposure and early physiological responses.

Critical Stages Affected by Heat Stress

The flower crop is most affected by heat stress at the reproductive stages of their production, particularly in flowering. The high temperatures disrupt the initiation, development and anthesis of buds and result in a severe loss of quality and flower drop (Jagadish, 2020). There is also an impact

on early stages of reproduction such as floral-primordia and bud differentiation. At these stages, heat suppresses meristem activity, typically resulting in a smaller number of inflorescences and high levels of buds that fail to reach maturity (Wang *et al.*, 2022).

Later stages of growth such as anthesis and opening of the flowers are rapidly aged by heat. It induces ethylene bursts and membrane destabilization that results in rapid abscission and pigment loss (Zhang *et al.*, 2023; Kumar, Jin, and Teng, 2023). Vegetative stages are greater in tolerance. Stress can be compensated by growth, yet the damage in any case decreases the amount of assimilates available to the reproductive organs. It is these variations that result in heatwaves during flowering having a devastating effect on the yield and quality in the market. Even brief exposures to heat may reduce the number of viable flowers by 30-70 percent in lilies and gerbera (Yang *et al.*, 2023). The table 1 gives the stage sensitivity of the key flower crops to heat stress and their subsequent yield and quality losses.

Table 1: Examples of Heat Stress Effects in Major Flower Crops

Flower Crop	Most Sensitive Stage to Heat Stress	Major Heat Stress Symptoms	Approximate Yield / Quality Reduction (%)	References
Rose	Anthesis and flower opening	Bud drop, petal wilting, red-to-pink fading	40–60	Zarif <i>et al.</i> , 2025
Chrysanthemum	Bud development	Flower abortion, yellowing of ray florets	30–50	Zhang <i>et al.</i> , 2023
Marigold	Flowering initiation	Premature floret drops, orange-to-dull fade	35–55	Kumar <i>et al.</i> , 2022
Carnation	Early bloom stage	Petal scorch, pink-to-white bleaching	45–65	Nakayama <i>et al.</i> , 2023
Gerbera	Flower stalk elongation	Stalk collapse, disc floret drops	40–60	Yang <i>et al.</i> , 2023

Note: Values represent typical field and greenhouse observations; actual reductions vary by cultivar, duration of stress, and management practices

Heat Stress–Induced Flower Drop

The flower drops as a result of heat stress implies early falling off of buds and flowers in crops like roses, petunias, and snapdragons, reducing the amount of yield that can be sold to the market by up to 60% at its peak (Kumar *et al.*, 2022). Hot climates accelerate the process of transpiration, which leads to the lack of water that undermines the support of the petals and develops abscission sites at the base of the flower (Yang *et al.*, 2023).

Meanwhile, supraoptimality of heat inhibits photosynthesis, decreasing carbohydrate energy to the reproductive sinks and denying developing buds the necessary energy reserves (Zhang *et al.*, 2023). This is aggravated by hormonal imbalance. Heat enhances the production of ethylene and reduces cytokinins and auxins, which are signals, which cause senescence and detachment (Jagadish, 2020; Kumar, Jin, and Teng, 2023).

Viability of pollen reduces drastically at above 35°C. The ovules that are produced by dysfunctional grains would not fertilize, and ultimately, the bud would abscise (Jagadish, 2020; Wang *et al.*, 2022). These interconnected disturbances are imbalance of water, lack of assimilates, hegemony of ethylene and failure of reproduction, lead to a cascading loss of flowers, turning lush crops into shabby, unprofitable crops.

Pigment Degradation under Heat Stress

Roses, orchids, and dahlias are also more valuable as the bright colors they have are due to anthocyanins and carotenoids. The heat degrades these pigments causing the petals to be faded and dull and the flowers will fetch 40-70% less (Zarif *et al.*, 2025). The presence of heat also inactivates the action of the enzymes involved in the formation of these pigments, such as chalcone synthase that form anthocyanins and phytoene synthase that form carotenoids, deactivating further pigment synthesis or halting it altogether (Zhang *et al.*, 2023).

The heat accelerates the degradation rate of the pigments by both directly denaturing the pigments and by activating hydrolytic enzymes that do so. The condition of oxidative stress is aggravated by heat since the reactive oxygen species formed in stressed chloroplasts and peroxisomes in the pigment molecules. It leads to bleaching and color imbalance (Kumar *et al.*, 2022; Zarif *et al.*, 2025).

When the temperature exceeds 38°C, the petals may fade away in a short period of time. Reds will turn to pink, yellows to beige and transformation will occur in a matter of several hours. These alterations make the flowers commercially inappropriate and demonstrate the impact of heat on profitability of flower farms (Yang *et al.*, 2023). Figure 2 summarizes the physiological and biochemical pathways between heat stress and flower drop and pigment degradation that occur in flower crops.

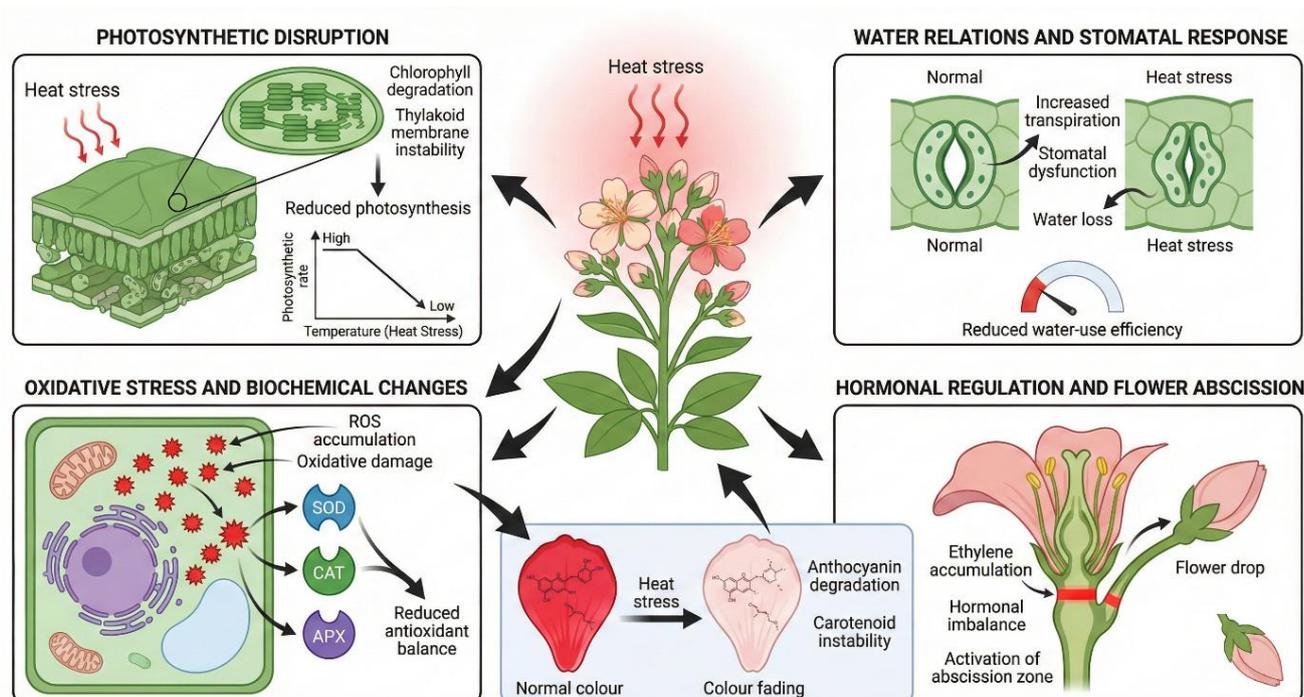


Figure 2: Physiological and biochemical mechanisms of heat stress–induced flower drop and pigment degradation in flower crops

Management Strategies to Reduce Heat Stress Effects

To overcome heat stress in flower crops, integrated management is necessary to ensure plants retain their flowers and preserve pigment integrity under increased temperatures (Kumar, Jin, and Teng, 2023). The grower ought to create accurate irrigation systems, which should be watered in the early morning or evenings to ensure turgor is upheld and loss of transpiration is minimized. Drip irrigation is particularly applicable to crops like the marigolds and gladiolus, which reduce evaporative loss (Yang *et al.*, 2023).

Organic mulches such as straw or coco peat reduce the soil temperature by 3-5 °C stabilizing the roots-zone conditions and increasing the uptake of nutrients. Direct sunlight may be limited by installing shade nets which block 30-50% of sunlight or more by relocating to some form of controlled cultivation e.g. greenhouses with air-flow. It eliminates peak heat waves that lead to the rise of ethylene and color loss (Kumar *et al.*, 2022). Strategies about nutrients focusing on potassium and calcium make cell walls and membranes strong. Abscission resistance can be enhanced by foliar sprays with KNO₃ or CaCl₂ (Kumar *et al.*, 2022). The automatic selection of heat-tolerant cultivars reduces the bud abortion and pigment deterioration, which provides more consistent functioning during the heat extremes to growers (Zarif *et al.*, 2025).

Conclusion

Flowers drop and pigments in crops like roses and chrysanthemums strongly drop in response to heat stress. Disrupted water balance, hormonal changes, and oxidative damage occur during the critical flowering period, the major problems. These impacts drastically lower the yields and downgrade the bright colours that command the plants high market prices posing increasingly difficult problems as climate variability amplifies heatwaves. Practical methods of maintaining a high quality of production include integrated solutions, like the improved irrigation, shading, nutrition, and the varieties that are heat-tolerant. Floriculturists should be able to react early in order to safeguard this sector that has a significant economic value against the increased heat pressure.

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HIDDEN REGULATORS OF FISH GENOME: PSEUDOGENES

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Abstract

Pseudogenes, once considered as junk DNA, has now known to contribute towards genome regulation and evolutionary processes. In fish, extensive genome duplication events, rapid diversification, and environmental adaptability make pseudogenes particularly informative for understanding genome evolution and physiological regulation. Recent studies have identified pseudogenes to be transcriptionally active and regulate the gene through ceRNA, small RNA and other epigenetic modulations. Their involvement in immune responses, stress adaptation, and disease conditions underscores their potential as molecular biomarkers for fish health and environmental monitoring. This article summarizes their classification, evolutionary significance following teleost-specific genome duplication. The relevance of pseudogene research to aquaculture is also discussed, highlighting its applications in genome annotation, transcriptomic analyses, and selective breeding.

Keywords: Pseudogenes; Fish genomics; Gene regulation; Aquaculture; Genome duplication

Introduction

Pseudogenes were long regarded as nonfunctional relics of evolution—mutated copies of genes that lost their protein-coding ability. However, advances in genomics and transcriptomics have revealed that pseudogenes can play important regulatory and evolutionary roles (Cheetham *et al.*, 2020). In fish, one of the most diverse vertebrate groups, pseudogenes provide valuable insights into genome evolution, adaptation, stress response, and disease resistance, with growing relevance to fisheries and aquaculture research (Zhang *et al.*, 2018; Pink *et al.*, 2011). Fish genomes are particularly informative for pseudogene studies due to whole-genome duplication events, rapid diversification, and environmental plasticity. Understanding pseudogenes in fish not only deepens evolutionary knowledge but also opens new avenues for biomarker discovery, selective breeding, and functional genomics in fisheries science.

What are Pseudogenes?

Pseudogenes are DNA sequences that resemble functional genes but contain mutations—such as frameshifts or premature stop codons—that prevent normal protein translation (Chen *et al.*, 2020). Based on their origin, pseudogenes are generally classified into three types:

1. Processed pseudogenes – formed by reverse transcription of mRNA and reintegration into the genome (retrotransposition)
2. Unprocessed (duplicated) pseudogenes – arise from gene duplication followed by functional decay
3. Unitary pseudogenes – formed when a functional gene becomes nonfunctional without duplication

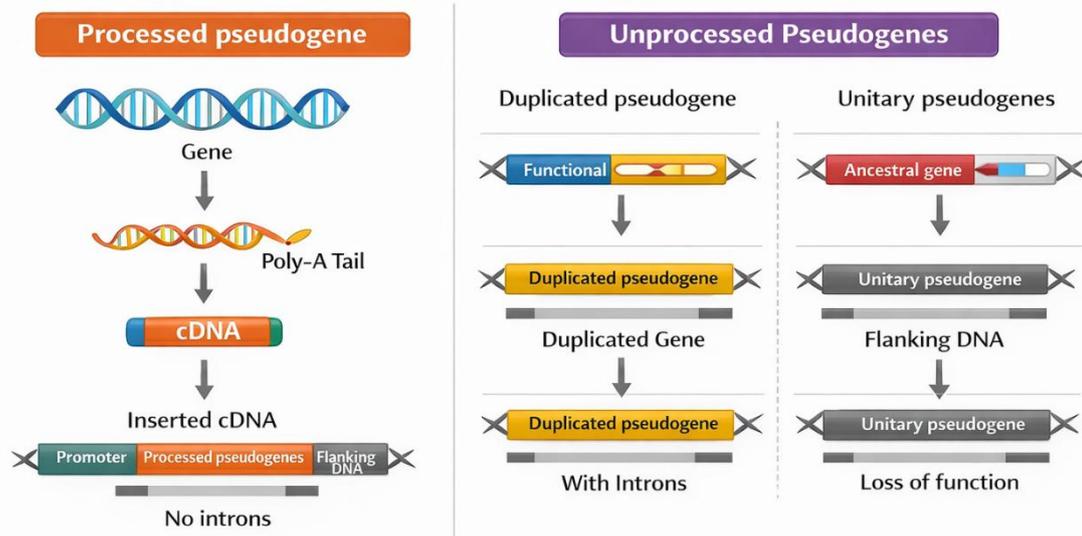


Fig. Classification of Pseudogenes: Processed, Duplicated and Unitary pseudogene

In fish genomes, duplicated pseudogenes are especially abundant due to teleost-specific genome duplication (TSGD) events (Braasch *et al.*, 2016).

Evolutionary Significance of Pseudogenes in Fish

Pseudogenes in fish result largely from the whole-genome duplication, gene duplication, and retrotransposition of teleost-specific genomes. After the teleost-specific genome duplication event, many duplicated gene copies underwent a relaxation of selection; over time, these copies accumulated a significant amount of mutations which allowed them to become pseudogenes. All pseudogenes produce, at minimum, evidence of a species' genome expanding, the loss of a gene and differences in the evolutionary divergence of related groups of fish (Glasauer and Neuhaus 2014; Braasch *et al.*, 2016). Processed pseudogenes also serve as an indicator of the dynamic nature of fish genomes; they arise when retrotransposed genes are inserted into a new location in the genome and do not carry any introns (Zhang *et al.*, 2018). Pseudogenes do have an effect on the adaptive evolution of organisms by providing regulatory control of other genes through the competing endogenous RNA mechanism (Pink *et al.*, 2011). The presence or absence of duplicated and unitary pseudogenes in fish illustrates how their functional requirements and ecological adaptations have evolved over time and will continue to do so (Braasch *et al.*, 2016).

Significance of pseudogenes

The fish immune system has evolved through extensive gene duplication, resulting in large immune gene families enriched with pseudogenes. The Toll-like receptor (TLR) families, for example, show expansion and diversification, with pseudogenization occurring in specific lineages due to relaxed selection and redundancy (e.g., TLR15 in vertebrates and multiple TLR8 paralogs in Atlantic salmon) (Neves *et al.*, 2022).

Cytokine and chemokine gene families also highlight the role of pseudogenes in immune responses. In salmonids, the IL1RL1 gene family includes both functional genes and pseudogenes linked to disease resistance against bacterial infections (Wang *et al.*, 2015; Nakharuthai *et al.*, 2016). While non-functional, these pseudogenes can influence immune responses or act as markers for functional variants.

Additionally, pseudogenes are involved in stress adaptation, growth, and life-history evolution. Genes such as myostatin and growth hormone show lineage-specific pseudogenization affecting muscle growth, while chorion-related genes in parental egg-care fish demonstrate adaptive loss under relaxed selection (Nagasawa *et al.*, 2025). In aquaculture, pseudogenes linked to the sex-determining gene *sdY* in Atlantic salmon complicate genetic sex identification (Ayllon *et al.*, 2020). Overall, fish pseudogenes are dynamic elements shaped by immune challenges and adaptive evolution.

Applications of Pseudogenes

- ❖ Genome Annotation - All genomic research depends heavily on accurate genome annotations, proper identification of pseudogenes is critical in this process
 1. Improves assembly quality and gene prediction
 2. Distinguish functional genes from pseudogenes
 3. Annotation of multigene families
- ❖ Transcriptomic Analysis - Gene expression studies in fish are typically conducted with transcriptomic techniques, such as RNA-sequence analysis. The presence of pseudogenes can complicate these analyses. However, if appropriately identified and analyzed, they will enhance the biological interpretation of results and contribute to a more complete understanding of the data generated (Paneru, 2017).
- ❖ Genomic Selection - Aquaculture has implemented various selective breeding programs that focus on enhancing the economic viability of aquaculture through the breeding of specific traits related to the fish's growth rate, efficiency in feeding, stress tolerance, and resistance to disease. The use of pseudogenes as genetic markers or potential regulators helps identify desirable traits in aquaculture stocks (Sangdehi *et al.*, 2024; Ayllon *et al.*, 2020).

Challenges in Aquaculture Genomics

Pseudogenes can complicate genome assembly and gene expression analysis due to sequence similarity with functional genes. Careful annotation is essential to avoid misinterpretation of results in breeding and functional studies.

Future Perspectives

The advent of long read sequencing, single cell RNA sequencing, and epigenome analysis could help pseudogene research to evolve rapidly. In future studies dealt with functional validation of pseudogenes, integration of pseudogenes in gene regulatory networks, comparative study of pseudogenes across the wild and cultured fish species could be done. Such efforts would enhance the understanding of fish biology and contribute to precision aquaculture and sustainable fisheries.

Conclusion

Pseudogenes recognized as functional and evolutionary molecular relic, contribute significantly in gene regulation, adaptation, stress response, and disease resistance making them highly relevant to fisheries and aquaculture research. Continued exploration of pseudogenes would provide novel insights into fish genome evolution and support the development of innovative strategies for fish health management and genetic improvement.

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IS ARTIFICIAL MEAT REAL?

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Abstract

The article focuses on artificial meat technology from the origin of the concept to its present status. Artificial meat technology includes both meat analogues and cultured meat. Cultured meat can be produced by tissue engineering or using genetically modified organisms. Various tissue engineering processes include scaffolding, self organizing techniques biophotonics etc. Various hurdles for commercializing the technology are high cost, reduced consumer acceptance and awareness as well as regulatory hurdles. In spite of these challenges it is the need of the hour due to ever increasing human population, the dwindling availability of land for animal husbandry as well as to prevent various illness arising out of red meat consumption.

Keywords: Artificial meat, cultured meat, tissue engineering, sustainability

Introduction

Have you ever imagined how wonderful it would be if you could have your nuggets and burger without feeling the guilt of animal sacrifice? Now you might end up pondering veg burger and soy nuggets. But what if the chicken in your burger comes from a lab? Yes! You heard it right, this is about artificial meat from its origin to the current scenario.

Meat analogues

Meat analogues include soybased food products like soy meat and tofu, fermented products like tempeh from soybean, quorn from *Fusarium venenatum* and kinema from *Bacillus*. However, all these fall under the purview of artificial meat. Soy meat is often revered for its high nutritional value appreciable texture and flavour similar to regular meat. Quorn is renowned for its low cholesterol and minimum saturated fat. Eventhough these products are accepted by fairly large section of society, they are a preferred choice of vegans.

Cultured meat

But the term artificial meat also encompasses cultured meat, produced by tissue engineering or genetically modified organisms produced by bio-engineering.

The first successfully cultured meat were that of goldfish and lamb. The methodology of tissue engineering ranges from scaffolding, self organizing techniques, to bioprinting, biophotonics and even some experiments have been done in nanotechnology but with limited success.

Scaffolding

In scaffolding, embryonic myoblasts are obtained through biopsy from the desired animal and they are cultured in plant based growth serum. Thereafter the stem cells are transferred to bioreactors and is allowed to proliferate and differentiate followed by transfer to scaffold - a frame on which the cells depending on environment initially develop into myotubes and then into myofibres. These myofibres are ready for consumption after normal cooking processes. Meat developed through this method is best suited for boneless meals like sausages and hamburgers. Selection of appropriate

culture medium which is of food grade, economic, easily available and providing ambient conditions for tissue proliferation as well as differentiation is of paramount importance. The essential components include amino acids, fatty acids, vitamins, trace minerals extracellular vesicles and antimicrobials. The scaffold material with highest performance was collagen. Direct perfusion bioreactors are the best suited for scaffold based meat culture.

Self organizing technique

In self-organizing technique explanted animal muscle tissue is used to develop more organized, well structured muscle tissue with foetal bovine serum as the common growth medium and horse serum as the differentiation medium.

Bioprinting

A more advanced technology is the 3D and 4D organ bioprinting. A Computer Aided Software (CAD) is used to create the prototype of the bioproduct. According to the CAD, cells are sprayed on gels, which then fuse on culturing to form the bio-product. The advantage of this technique is the development of vascular tissue for blood transportation. In 4D organ bioprinting alteration with time factor is also considered in addition to the above mentioned.

Biophotonics is a novel technique employing laser light in order to bind particles. It serves as an alternative to scaffolds.

Hurdles for commercialization

These techniques even though groundbreaking, face significant challenges with regard to commercialization, the major one being the production cost. The first hamburger produced in lab took 2 years to be developed at the cost of \$3,00,000 in 2013. By 2020, the costs were cut down significantly to the tune of \$35/burger. Regulatory and health concerns are also hindering the widescale adoption of the product. Legalising artificial meat also opens up the possibility of food adulteration by mislabelling of artificial meat as cultured meat and vice versa. The use of non livestock species for meat production is also associated with risk of DNA transfer through artificial cell lines. The absence of colour and texture in case of artificial meat is a prima facie factor which can hamper consumer acceptance and must be supplemented either by addition of sugar beet saffron or other alternatives. Nutritional value, texture, flavour etc must be at par with natural meat for enhancing consumer acceptance and surviving the market competition.

Genetically modified organisms

Genetically modified organisms is yet another source of artificial meat, the common examples being Enviropigs for omega 3 fatty acid synthesis and GalSafe pig devoid of alpa-gal sugar, a potent allergen. GalSafe pigs by Revivicor, are the first genetically altered animals approved by FDA for consumption. Even though GMO meat resembles it's natural counterpart in every aspect adoption remains quite low in many regions due to ethno-cultural reasons and health concerns.

In December 2020, Singapore became the first country to grant regulatory clearances to lab grown meat by approving the company 'Eat Just' with chicken nuggets being its first commercial product. US Drug and Food Administration approved GOOD Meat and UPSIDE Foods to market cell cultivated chicken in 2023.

Conclusion

Despite the higher production cost, regulatory tussles the further development of this technology is a necessity primarily due to the rising global population and food requisites. Artificial meat technology is an important milestone in the direction of animal welfare and environmental sustainability. Livestock being a major factor associated with emission of green house gases,

switching to artificial meat technology can help cut emission levels provide non conventional energy sources are being utilised for its production. It also serves as a solution for non communicable diseases arising out of red meat consumption like colorectal cancer, cardiac arrest, cardiovascular illness and diabetes. The risk of contamination by pesticides, bacteria, toxic metals etc can be reduced to a great extent.

For further development there must be enhanced support from government agencies, and consumer awareness and robust research in this arena.

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(source: Mateti, T., Laha, A. & Shenoy, P. Artificial Meat Industry: Production Methodology, Challenges, and Future. JOM 74, 3428–3444 (2022). <https://doi.org/10.1007/s11837-022-05316-x>)

FUNCTIONAL NUTRITION THROUGH DIET TRENDS: INSIGHTS INTO KETO, PALEO AND LOW-CARB DIETS

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Abstract

Diet-based nutritional approaches such as the ketogenic, paleo and low-carbohydrate diets have gained substantial global popularity due to their perceived health benefits, particularly in weight management and metabolic health. This article critically examines the principles, popularity drivers, health outcomes and limitations associated with these contemporary dietary patterns. The ketogenic diet, characterized by high fat and very low carbohydrate intake, promotes ketosis and has been associated with short-term fat loss and metabolic improvements, though concerns remain regarding long-term sustainability and nutritional adequacy. The paleo diet emphasizes whole, unprocessed foods while excluding grains and refined sugars, appealing to consumers seeking “natural” dietary practices, yet lacks robust long-term clinical evidence. Low-carbohydrate diets, including the Atkins diet, have a long history of use and demonstrate benefits in weight reduction and glycemic control, particularly among individuals with type 2 diabetes. Despite their popularity, these diets are often restrictive and may lead to nutrient deficiencies and variable health outcomes among individuals.

Keywords: Ketogenic diet, Paleo diet, Low-carbohydrate diet, Weight management, Metabolic health, Personalized nutrition, Dietary trends.

Introduction

The continued popularity of diet-based products, particularly those associated with Keto, Paleo and Low-Carb diets, can be attributed to their perceived health benefits and the influence of cultural trends. These diets have gained traction due to their potential for weight loss, metabolic benefits and the influence of media and celebrity endorsements. Each diet has unique characteristics that appeal to different consumer needs and preferences, contributing to their sustained popularity in the market.

Ketogenic Diet

The ketogenic diet (KD) is characterised by high-fat and low-carbohydrate intake, which induces a metabolic state known as ketosis. This process helps in fat loss and may preserve lean muscle mass, making it appealing for body composition improvement (Malhotra & Sawal, 2023) (Mellenia & Santoso, 2024). However, the long-term sustainability and health implications of such restrictive diets remain a topic of debate among nutrition experts (Tahreem *et al.*, 2022). Critics argue that while these diets may offer short-term results, they often lack the necessary nutritional balance and can lead to adverse health effects over time (Tahreem *et al.*, 2022). The diet has gained popularity through celebrity endorsements and social media, significantly contributing to its resurgence as a weight loss method (Gemmill *et al.*, 2020). Additionally, the ketogenic diet's appeal is enhanced by

its portrayal as a quick fix for weight loss, despite concerns regarding its long-term health effects (Tahreem *et al.*, 2022).

Despite its popularity, the long-term effects and sustainability of the ketogenic diet remain subjects of debate, with individual responses varying based on genetic and lifestyle factors (Mellena & Santoso, 2024). As personalized nutrition becomes more prominent, understanding the genetic and phenotypic influences on dietary responses is crucial for developing effective dietary interventions (Gibney, 2020). This complexity highlights the need for tailored approaches to ensure optimal health outcomes for individuals following such diets. Furthermore, the ketogenic diet may pose risks such as nutrient deficiencies and cardiovascular concerns, emphasizing the importance of a balanced approach to dietary planning (Khairunnisa, 2025).

Paleo Diet

The Paleo diet emphasizes whole foods and eliminates processed foods, grains and sugars, aligning with the dietary patterns of early humans. This diet is often marketed as a natural and healthy way to eat, which appeals to consumers seeking a return to more traditional eating habits (Wendy & Wu, 2023). While the Paleo diet promotes a return to natural eating, it too faces scrutiny regarding its long-term health impacts and nutritional adequacy, similar to the ketogenic approach. Most literature available on paleo diets concludes that the Paleo diet shares similarities with the ketogenic diet in its low-carbohydrate approach, which can contribute to weight loss and improved metabolic health (Wendy & Wu, 2023). However, the lack of comprehensive research on the long-term effects of the Paleo diet raises concerns about its sustainability and potential health risks, similar to those noted for the ketogenic diet (Khairunnisa, 2025).

Low-Carb Diets

Low-carbohydrate diets (LCDs) have been popular for over a century, cycling in and out of fashion. They are associated with weight loss and improvements in metabolic markers such as triglycerides and HDL cholesterol (Westman *et al.*, 2003) (Goldberg & Bucciarelli, 2006). However, the effectiveness and safety of these diets can vary significantly among individuals, necessitating personalized dietary strategies to optimize health outcomes.

The Atkins diet, a well-known low-carb diet, has significantly influenced consumer behavior, leading to the creation of new markets for low-carb products in groceries, restaurants, and other food industries (Maresco, 2005). As the landscape of nutrition continues to evolve, personalized approaches that consider genetic and lifestyle factors are becoming essential for maximizing the benefits of low-carb diets (Singar *et al.*, 2024) (Khairunnisa, 2025).

Despite fluctuations in popularity, low-carb diets continue to be a viable option for weight management and glycemic control, particularly in individuals with type 2 diabetes (Alkhunein *et al.*, 2024) (Wylie-Rosett & Davis, 2009). Research indicates that low-carb diets can effectively improve glycemic control in individuals with type 2 diabetes, but their long-term sustainability and health implications require further investigation. (Palumbo, 2001) . Moreover, the existing literature suggests that while low-carb diets can enhance short-term glycemic control, their long-term effects on overall health and mortality remain uncertain (Alkhunein *et al.*, 2024). Further studies are essential to clarify these outcomes and establish guidelines for safe, sustainable dietary practices.

Conclusion

The popularity of these diets is not without challenges. Critics argue that the restrictive nature of these diets can lead to nutritional deficiencies and may not be sustainable in the long term. Additionally, the effectiveness of these diets can vary widely among individuals, necessitating

personalized dietary planning to ensure safety and efficacy. As research continues to evolve, it is crucial to balance the benefits of these diets with potential risks and to consider individual health needs and preferences when adopting such dietary patterns.

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CHANGING CONSUMER PREFERENCES: THE GLOBAL RISE OF READY-TO-COOK AND SALAD VEGETABLES

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Abstract

Rapid urbanisation, changing eating habits, growing health consciousness, and increased demand for easy food alternatives have all contributed to a major shift in the worldwide vegetable industry. Within this context, salad and ready-to-cook (RTC) veggies have become one of the most active and quickly growing sectors. Because of its ease, nutritional value, and adaptability, baby corn, cherry tomatoes, exotic cucumbers, and lettuce blends are the most popular items on contemporary retail shelves. Once regarded as niche, these items are now widely available as customers seek fresh, clean, and convenient veggies that fit their hectic schedules. This article investigates major market drivers, looks at consumer psychology, evaluates the behavioural, economic, and societal changes that have led to the growth of RTC and salad veggies, and talks about the prospects for this rapidly expanding business.

Introduction

The way humans choose, prepare, and consume food has changed dramatically, as seen by the current global food system. Convenient foods without sacrificing nutrients are preferred by modern customers, particularly in metropolitan and semi-urban areas. The ready-to-cook and salad vegetable market, which provides fresh, pre-cleaned, and frequently pre-cut produce meant to reduce preparation time, has experienced exceptional growth as a result of this shift. Because of their adaptability, attractive look, and simplicity of ingestion, vegetables, including baby corn, cherry tomatoes, exotic cucumbers, and various lettuce mixtures, have become mainstays in contemporary kitchens. The prevalence of dual-income households, shifting lifestyles, and increased knowledge of diet-related health issues all contribute significantly to their rise. This article provides a thorough analysis of how consumer preferences have changed, what drives the demand for these veggies, and what trends are expected to influence this dynamic industry going forward.



Changing Consumer Preferences

Factors Influencing Consumer Behaviour

Salad veggies are becoming more and more popular due to several lifestyle and socioeconomic factors:

- **Busy Urban Lives:** Convenient, time-saving eating alternatives are now necessary due to longer workdays and hectic schedules. RTC veggies let customers to keep a diversified diet while drastically cutting down on preparation time.
- **Health Consciousness:** Foods high in nutrients, fiber, and antioxidants that promote digestion, immunity, and general well-being are given priority by consumers. These advantages are offered by RTC and salad veggies, which are simple to incorporate into regular meals.
- **Trends in Clean Eating:** Hygienically packed fresh-cut veggies and salad mixtures are becoming more popular as people become more conscious of chemical residues and items devoid of pesticides. **Nuclear Families and Working Women:** The need for easy, portion-controlled, ready-to-use veggies that minimize food waste is driven by smaller family sizes and dual-income households.
- **Global Cuisine Exposure:** Consumers are influenced to include salads, stir-fries, and unusual vegetable preparations in their meals by having access to international cuisines and culinary media.
- **Online Marketplaces for Groceries:** Urban customers now have greater accessibility and convenience thanks to subscription-based services, home delivery, and carefully chosen fresh vegetable bundles.

Consumer Segmentation

- 1) **Urban Youth:** Display a fondness for health-conscious pre-packaged veggie kits, salad bowls, and smoothie mixes.
- 2) **Working Professionals:** To make fast meals, use pre-cut and portion-controlled veggies.
- 3) **Elderly Consumers:** RTC veggies are more convenient and need less preparation.
- 4) **Health-Conscious Families:** Include freshly cut veggies in everyday meals to provide a balanced diet and regular vitamin and mineral consumption.

Ready-to-Cook and Salad Vegetables: Definitions and Scope

Ready-to-Cook (RTC) Vegetables

Produce that has been cleaned, trimmed, chopped, or portioned for quick cooking is referred to as RTC veggies. Important instances consist of:

- Vegetables that have been pre-washed and cut for mixed meals
- Mixes tailored to a particular dish, including stir-fry kits, curry, or sambar
- Pre-cut gourds, pumpkin, brinjal, and okra; peeled roots and tubers, such as carrot, beetroot, and ginger

Ready-to-Eat (RTE) Salad Vegetables

Salad veggies are prepared for raw eating, pre-washed, and undergo little processing. Examples consist of:

- Iceberg, romaine, butterhead, and oak leaf lettuce mixes; spinach, baby spinach, kale, and arugula leafy greens

- Finished salad bowls with dressings, toppings, and garnishes; • Shredded vegetables, such as cabbage, carrots, and beets

Factors Driving Market Growth

- 1) Convenience and Time Savings: Fast-paced metropolitan lives are met with pre-cut and pre-washed veggies, which drastically cut down on meal preparation time.
- 2) Health and Nutrition: Essential vitamins, minerals, antioxidants, and nutritional fibre are retained in RTC and salad veggies.
- 3) Hygiene and Food Safety: Safe consumption is ensured by proper sanitisation and packaging, which lowers the danger of microbiological infection.
- 4) Visual Appeal: Consumer sense of freshness is improved by uniform forms, vivid colours, and sharp textures.
- 5) Salad Culture and Fitness Trends: The popularity of detox diets, smoothie bowls, and salads has led to an increase in demand.
- 6) Retail and E-Commerce Growth: Supermarkets and internet sites provide home delivery and subscription services, making them more accessible.

Market Dynamics of Popular Vegetables

5.1 Baby Corn : Tender, mildly flavoured, adaptable for salads, soups, and stir-fries, with a great potential for export and a longer shelf life.

5.2 Cherry Tomatoes : Used in salads, garnishes, and ready-to-eat snacks, it's sweet, colourful, and perfect for eating raw.

5.3 Unusual Cucumbers : Small, crisp, and seedless; used as a garnish, in salads, sandwiches, and infused water.

5.4 Mixes of Lettuce : Fresh salads, sandwich fillings, and meal packages may be made with romaine, iceberg, butterhead, and oak leaf kinds.

Retail Innovations and Supply Chain Enhancements

1. Modern Production Systems: Consistently high-quality, chemical-free veggies are produced using hydroponics, vertical farming, insect-proof netting, and greenhouses.
2. Minimal Processing Methods: Cleaning, cutting, trimming, and sanitary packing prolong shelf life without sacrificing freshness.
3. Modified Atmosphere Packaging (MAP): Slows microbial growth and respiration by controlling O₂, CO₂, and N₂ levels.
4. Cold Chain Logistics: Perishable product is preserved by pre-cooling, refrigerated transportation, and storage.
5. Traceability and Smart Packaging: Consumers are informed about origin, handling, and freshness using QR codes and sensors.
6. Private Brands and Startups: Recipe cards, salad kits, and carefully chosen vegetable packs are available from supermarkets and up-and-coming companies.

Benefits of RTC and Salad Vegetables

1. Time Efficiency: Significantly cuts down on preparation and cooking time.
2. Less Food Waste: Portion-controlled packaging reduces food waste in homes.
3. Consistency and Quality: Reliable cooking outcomes are guaranteed by uniformity in size, texture, and freshness.
4. Hygiene and Safety: Packaging and sanitisation procedures reduce the chance of contamination.
5. Nutritional Value: Preserves vital nutrients for consumption that are health-conscious.

Challenges

1. High Perishability: Requires rigorous cold-chain management.
2. Production Costs: Advanced packaging, cold storage, and skilled labour increase costs.
3. Maintaining Hygiene: Microbial contamination during processing can affect product safety.
4. Consumer Perception: Some consumers perceive whole vegetables as fresher than pre-cut options.

Technological Innovations

1. Edible Coatings: By lowering moisture loss and oxidative reactions, aloe vera, chitosan, whey proteins, and plant gums increase shelf life.
2. Freshness Sensors: Consumers receive real-time quality information via indicators integrated into packaging.
3. Advanced Sanitisation Techniques: Electrolysed water, ozone, and UV treatment lower bacteria burden without leaving behind chemical residues.
4. Breeding Varieties for Fresh-Cut Markets: Selection for firmness, delayed browning, and longer shelf life enhances appropriateness for salad and RTC applications.

Market Trends and Economic Potential

1. Supermarket Growth: Fresh-cut vegetable-focused refrigerated areas improve customer access.
 1. Online Subscription Models: Curated packs and home delivery offer regular supply and convenience.
 2. Salad bars and health cafes: Encourage people to consume fresh salads and raise awareness of the need to eat healthily.
 3. Customised Meal Kits: Vegetable kits that are protein-focused, low-carb, detox, or keto-friendly satisfy certain nutritional needs.
 4. Export Opportunities: Countries such as India, Thailand, and China export superior RTC and salad veggies to worldwide markets.

Future Prospects

1. Urban Expansion: Demand for RTC and salad vegetables is anticipated to increase in Tier-II and Tier-III cities.
2. Smart Packaging Innovations: Materials that indicate spoiling and regulate temperature will boost customer confidence.
3. Integration with Urban Agriculture: Ultra-fresh vegetables will be provided by rooftop farms and vertical farming systems.
4. Organic and Residue-Free Options: Certified organic veggies will become more popular owing to health-conscious consumers.
5. Customized Meal Kits: By focusing on certain age groups, dietary preferences, and health requirements, the market will grow.

Conclusion

The increased emphasis on convenience, health, nutrition, and food safety is driving a fundamental shift in worldwide dietary behaviour, which is reflected in the development of ready-to-cook and salad veggies. Baby maize, cherry tomatoes, exotic cucumbers, and lettuce mixtures are examples of vegetables that have emerged as important emblems of this change, providing customers with fresh, sanitary, aesthetically pleasing, and simple alternatives that fit nicely with fast-paced urban lifestyles. Advances in protected culture, hydroponics, cold-chain logistics, and modified-

atmosphere packaging, which guarantee year-round supply, longer shelf life, and better product quality, contribute to their growing appeal. Simultaneously, the popularity of salads, stir-fry mixes, and minimally processed vegetable products has increased due to exposure to other cuisines, the impact of food media, and the growth of wellness-oriented eating habits. Ongoing advancements in agricultural techniques, supply chain management, and packaging technologies are gradually closing these gaps, even if there are still obstacles to overcome, especially those pertaining to perishability, production costs, and maintaining cleanliness in processing and distribution. Farmers, entrepreneurs, retailers, and exporters may profit economically from this market sector by taking advantage of the rising demand for high-quality, ready-to-use veggies. With enhanced infrastructure, strategic market expansion, and changing customer expectations, the ready-to-cook and salad vegetable industry is expected to grow steadily and resiliently in the future. Stakeholders along the value chain can guarantee that RTC and salad veggies remain a contemporary, wholesome, and sustainable option for urban food consumption in the future by concentrating on quality assurance, transparent sourcing, sustainability, and effective distribution.

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JASMONIC ACID INDUCED DEFENSE MECHANISMS AGAINST INSECT PESTS IN CHICKPEA

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Abstract

Chickpea (*Cicer arietinum* L.) is one of the most important and nutritious legume crops. It is often severely affected by insect pests, particularly the gram pod borer (*Helicoverpa armigera*), leading to significant yield losses. Jasmonic acid plays a central role in regulating plant defense responses against insect herbivory. Upon insect attack, JA biosynthesis and signaling are rapidly activated, resulting in the induction of direct defenses such as proteinase inhibitors, secondary metabolites, oxidative burst and strengthening of physical barriers. JA also mediates indirect defenses through the emission of herbivore-induced plant volatiles that attract natural enemies. Understanding JA-induced defense mechanisms provides opportunities for developing sustainable pest management strategies in chickpea.

Keywords: Chickpea, Jasmonic acid, induced defense, *Helicoverpa armigera*

Introduction

Chickpea is an important legume crop grown around the world and serves as a key protein source, especially for people in South Asia, Africa, and Mediterranean countries. Unfortunately, chickpea cultivation faces major challenges from insect pests, especially the gram pod borer (*Helicoverpa armigera*, Hübner), which can cause substantial yield losses if not managed effectively. In response to insect herbivory, plants activate a suite of defense mechanisms regulated by phytohormones. One particularly important hormone in this defense system is Jasmonic acid (JA), which helps plants fight back against insects that chew on them. JA is part of the octadecanoid pathway and functions both as a local defender and a systemic signaler, prompting biochemical and molecular changes that enhance resistance to insect attack (Sane *et al.*, 2025).

Jasmonic acid biosynthesis and signaling

The plant produces Jasmonic acid starting from α -linolenic acid through enzymes like LOX, AOS, and AOC, creating JA and its stronger form JA-Ile. When insects damage the plant, JA and JA-Ile levels quickly rise at the injured area, starting a chain reaction inside cells. JA-Ile attaches to COI1-JAZ receptors, which breaks down JAZ proteins and releases transcription factors such as MYC. These factors then switch on defense genes that change how the plant functions and protects itself against attacking insects. This cascade effectively amplifies the defense response to herbivore attack.

Chickpea plants demonstrate rapid defense responses when exposed to simulated insect damage through oral secretions and physical injury. This triggers immediate activation of JA-related genes within minutes. The resulting JA production serves as a critical defense signal that diminishes

herbivore attraction, survival, and reproductive success. Plant defenses operate through two mechanisms: direct and indirect response. Direct responses create deterrent compounds and protective proteins at injury sites that discourage feeding and egg-laying while impairing insect development; indirect responses emit specific volatile compounds that recruit herbivore predators (Karban, 2011) (Fig 1). Together, these complementary strategies form an integrated defense network protecting plants from continued herbivore damage.

Direct Defense Mechanisms Activated by JA

Induction of Defensive Proteins: One of the primary outcomes of JA signaling in plants is the induction of defensive proteins, such as proteinase inhibitors (PIs), which inhibit insect digestive enzymes. PIs reduce the ability of insect pests to process plant proteins, thus slowing larval growth and reducing survival.

Secondary Metabolite Accumulation: JA triggers the accumulation of secondary metabolites, including phenolics, flavonoids, tannins, and phytoalexins, which can act as antifeedants or toxins to insect herbivores. In chickpea, herbivory has been associated with an up-regulation of genes in the phenylpropanoid pathway and increased synthesis of flavonoids compounds known to negatively affect insect digestive physiology and deter feeding.

Oxidative Burst and Detoxification Enzymes: Chickpea shows rapid up-regulation of reactive oxygen species, ROS-related genes, along with defensive enzymes that manage oxidative stress, such as peroxidases and superoxide dismutase, which help balance signaling and cellular protection.

Indirect Defense Mechanisms Activated by JA

Volatile Organic Compounds (VOCs): Beyond direct defenses, JA plays a key role in indirect plant defense by stimulating the emission of herbivore-induced plant volatiles (HIPVs). These VOCs can attract natural enemies of herbivorous pests, such as parasitoids and predatory insects, enhancing tritrophic interactions that suppress pest populations.

Systemic Signaling: JA not only acts locally at the wound site but also contributes to systemic signaling, leading to induced resistance in undamaged parts of the plant. The long-distance transport and signaling functions of JA enhance overall plant defense plasticity.

Crosstalk with Other Hormonal Pathways

Plant defense signaling is a network of interacting hormones. In chickpea, ethylene (ET) often works synergistically with JA to amplify defense responses, while salicylic acid (SA) can act antagonistically in some contexts (Zhang *et al.*, 2025). Studies indicate simultaneous up-regulation of JA and ET pathways shortly after wounding, enabling integrated defense responses. JA-ET crosstalk enhances expression of defense genes and might reduce SA-mediated suppression of JA responses, providing stronger protection against chewing pests (Pandey *et al.*, 2017).

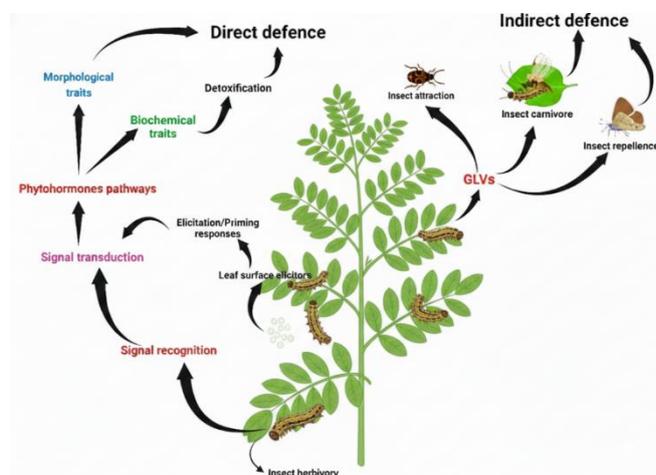


Fig 1: JA mediated defense responses against *H. armigera* in chickpea

JA and Chickpea Pest Management

Given the central role of JA in plant defense, exogenous application of JA or its derivatives has been explored as a strategy to enhance resistance in crops. While most evidence comes from model plants and cereals, analogous approaches in chickpea could potentially boost defensive enzyme activities and metabolic defenses, reducing reliance on chemical insecticides. Exogenous JA application has been shown in other crops to enhance resistance against herbivores and can improve yield under pest pressure by pre-activating defense pathways. Developing JA-based treatments or breeding chickpea cultivars with enhanced JA responsiveness could be integrated with other pest management strategies (El Wakeil *et al.*, 2010). However, the growth defense trade-off should be considered; over-activation of defense responses can divert energy away from growth and yield.

Conclusions and Future Perspectives

Jasmonic acid is a pivotal regulator of defense mechanisms in chickpea, activating a broad range of direct defenses (secondary metabolites, defensive proteins, oxidative responses) and indirect defenses (VOC emission, systemic signaling) that collectively reduce insect damage. JA interacts with other hormonal pathways to orchestrate a balanced and effective response to herbivory. While much of the mechanistic understanding comes from broader plant biology studies, emerging transcriptomic and physiological research in chickpea reinforces the importance of JA-mediated responses during insect attack.

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LINKING POSTHARVEST MANAGEMENT WITH MARKET PRICE REALISATION

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Abstract

Postharvest losses in fruits and vegetables range from 20-40% in India, directly affecting farmers' income and national food security. While production technologies have advanced significantly, poor postharvest management remains a major bottleneck in achieving better market prices. This article explains how scientific postharvest management is directly linked with market price realisation, highlighting critical operations such as harvesting at proper maturity, grading, packaging, storage, transportation, and value addition. Emphasis is given to what to do, when to do it, why it matters, and how it improves price realisation, supported by practical field recommendations.

Introduction

Agriculture is often described as the backbone of many economies, particularly in developing nations where a significant portion of the population depends directly or indirectly on farming for their livelihood. It provides food, raw materials, and employment, and it sustains rural communities. Yet, despite the central role of agriculture, farmers frequently struggle to earn fair prices for their produce. This paradox arises because the value of crops is not determined solely at the point of harvest. Instead, it is shaped by what happens after the critical stage known as postharvest management.

Postharvest management refers to the collection of practices and technologies that govern how crops are handled once they leave the field. This includes cleaning, sorting, grading, drying, packaging, storage, transportation, and even processing. Each of these steps influences the quality, shelf life, and marketability of agricultural products. For example, grains stored in poor conditions may develop mould or pest infestations, fruits bruised during transport may lose their appeal to consumers, and vegetables left without refrigeration may spoil before reaching the market. These losses are not just physical; they translate directly into financial losses for farmers, reducing the prices they can command and limiting their bargaining power. The importance of postharvest management becomes clearer when we consider the scale of losses. Studies suggest that between 30 and 40 per cent of food produced globally is lost or wasted before it reaches consumers, with many of these losses occurring after harvest in developing countries. This is not merely a matter of inefficiency, and it is a direct drain on farmer incomes and national food security. When crops are wasted, farmers lose potential revenue, consumers face higher prices, and nations struggle with food shortages. Thus, postharvest management is not just a technical issue; it is a matter of economic stability and social well-being.

Market price realisation, the actual price farmers receive when they sell their produce, is closely tied to postharvest practices. High-quality produce that is well-handled, properly stored, and attractively packaged fetches better prices in both local and international markets. Conversely, poor handling reduces quality and forces farmers into distress sales at lower prices. For instance, a farmer who can store grains safely may choose to sell them later when market demand is higher, thereby earning more. Similarly, a fruit grower who invests in cold storage and careful packaging can access premium urban or export markets, where buyers are willing to pay extra for freshness and uniformity. Unfortunately, discussions around agriculture often focus narrowly on inputs such as seeds, fertilisers, irrigation, and mechanisation. While these are important for boosting production, they overlook the fact that production alone does not guarantee prosperity. The journey from farm to market is equally critical, and without proper postharvest management, much of the farmer's hard work is wasted. Linking postharvest management with market price realisation is therefore essential. It ensures that farmers not only produce more but also earn more, creating a virtuous cycle of prosperity, investment, and sustainability.

In essence, postharvest management is the bridge between farmer effort and farmer reward. It determines whether crops are sold at their true value or at a discount due to spoilage and poor quality. By strengthening this link, societies can move closer to achieving food security, reducing waste, and ensuring that farmers receive fair compensation for their labour. This is why postharvest management must be seen not as a secondary concern but as a central pillar of agricultural development and economic growth.

Scale of Postharvest Losses

Globally, it is estimated that between 30 and 40 per cent of food produced is lost or wasted before it reaches consumers. In developing countries, these losses are concentrated at the postharvest stage due to inadequate infrastructure, poor handling practices, and lack of awareness. Grains may spoil in storage, fruits and vegetables may rot during transportation, and milk may curdle without proper cooling. These losses not only reduce the quantity of food available but also diminish its quality, leading to lower prices in the market. For farmers, this translates into reduced income and, in many cases, financial distress. The link between postharvest losses and market price realisation is direct: poor management reduces both supply and quality, forcing farmers to sell at lower rates or even discard their produce.

Quality as a determinant of price

Markets reward quality. Buyers, whether local consumers or international importers, are willing to pay premiums for produce that is fresh, uniform, and safe. Postharvest management practices such as sorting, grading, and packaging directly influence the perception of quality. For example, mangoes that are carefully graded by size and colour fetch higher prices in export markets compared to mixed, ungraded batches. Similarly, rice stored in hermetic bags that prevent pest infestation commands better rates than rice damaged by insects. Quality is not just about appearance; it is about meeting consumer expectations and market standards. Farmers who invest in postharvest management are essentially investing in quality, which translates into better price realisation.

Timing and Market dynamics

Agricultural markets are highly sensitive to timing. Prices fluctuate based on supply and demand, and farmers who can store their produce safely gain the advantage of selling when prices peak. For instance, tomato farmers in India often face distress sales during peak harvest when supply floods

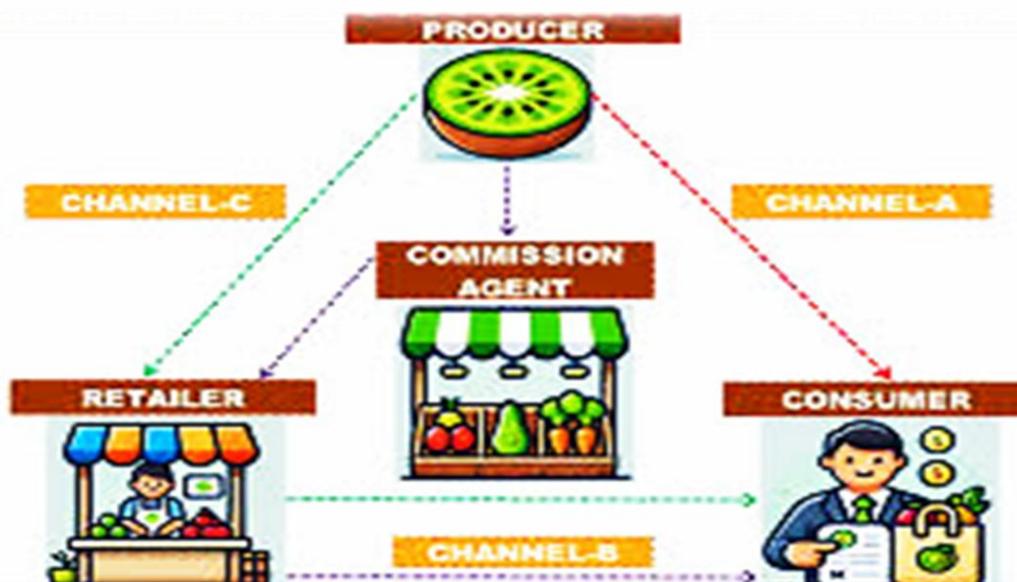
the market. However, those with access to cold storage can delay sales and earn 20-30 per cent more by selling off-season. Postharvest management thus acts as a tool for market timing, allowing farmers to align their sales with favourable price conditions. Without proper storage, farmers are forced into immediate sales, often at low prices, which undermines their income potential.

Storage and Infrastructure Challenges

Storage is one of the most critical aspects of postharvest management. Inadequate storage facilities lead to spoilage, pest infestation, and quality deterioration. Traditional storage methods, such as open granaries or jute bags, expose grains to moisture and pests. Modern solutions like hermetic bags, silos, and cold storage units significantly reduce losses. However, access to such infrastructure remains limited in many rural areas. The lack of storage forces farmers to sell immediately after harvest, often when prices are lowest. This infrastructure gap highlights the importance of linking postharvest management with market systems. Investments in rural storage facilities can transform farmer incomes by enabling better price realisation.

Packaging and Transportation

Packaging is often underestimated in agriculture, yet it plays a vital role in preserving quality and attracting buyers. Ventilated crates for fruits and vegetables reduce spoilage compared to traditional sacks. Eco-friendly packaging appeals to environmentally conscious consumers and can fetch higher prices in niche markets. Transportation is equally important. Poor roads, delays, and a lack of refrigerated trucks lead to significant losses, especially for perishable commodities. Efficient logistics ensure that produce reaches markets in good condition, enhancing both quality and price. Farmers who adopt better packaging and transportation practices are more likely to access premium markets and earn higher returns.



Case studies of success

Several examples illustrate the link between postharvest management and market price realisation. In Kenya, mango exporters adopted hot water treatment and strict grading standards to meet European Union requirements. As a result, they gained access to lucrative export markets, doubling farmer incomes. In Southeast Asia, rice farmers using hermetic storage reduced losses by 15 per

cent, stabilising prices and improving household income. In India, tomato farmers with access to cold storage earned significantly more by selling off-season. These cases demonstrate that postharvest management is not just about reducing losses; it is about unlocking new opportunities and higher value.

Value addition and Processing

Postharvest management extends beyond storage and transport. Processing, such as drying, milling, juicing, or packaging, adds value to raw produce. Farmers who process their crops can access new markets and earn higher prices. For example, turning milk into cheese or yoghurt extends shelf life and increases profitability. Drying fruits creates products that can be sold year-round. Milling grains into flour opens urban markets. Value addition transforms agriculture from subsistence to enterprise, linking postharvest practices directly with market price realisation.

Policy and Innovation

Governments and private players have a crucial role in strengthening the link between postharvest management and market price realisation. Policies that support rural infrastructure, cold chains, and farmer cooperatives can make a significant difference. Innovations such as solar-powered storage units, mobile cold rooms, and digital platforms connecting farmers directly to buyers are changing the landscape. Startups are offering affordable solutions that empower smallholders to manage postharvest challenges effectively. By integrating policy support with technological innovation, countries can ensure that farmers benefit from better price realisation.

Conclusion

Postharvest management is the missing link between hard work in the field and fair reward in the market. Farmers who adopt better practices in harvesting, storage, packaging, and transport are not just reducing losses; they are strategically positioning their produce for maximum value. Linking postharvest management with market price realisation is essential for farmer prosperity, food security, and sustainable development. It is time to shift the focus from production alone to the entire value chain, ensuring that farmers reap the full benefits of their labour. Beyond reducing losses, effective postharvest management also enhances market competitiveness. Farmers who consistently deliver high-quality produce build trust with buyers, traders, and consumers. This reputation allows them to secure long-term contracts, access premium markets, and negotiate better prices. In many cases, buyers prefer reliable suppliers over cheaper but inconsistent sources, which means that farmers who invest in postharvest practices gain stability in their income. Another important point is the role of postharvest management in export readiness. International markets demand strict compliance with quality, safety, and packaging standards. Without proper handling, farmers are excluded from these lucrative opportunities. By adopting modern postharvest technologies, farmers can meet global standards, diversify their markets, and earn foreign exchange for their countries. This not only benefits individual farmers but also strengthens national economies.

Postharvest management also contributes to environmental sustainability. Reducing food losses means fewer resources, such as water, fertilisers, and energy, are wasted. It minimises greenhouse gas emissions from decomposing food and reduces pressure on land and ecosystems. In this way, better postharvest practices align with climate-smart agriculture and global sustainability goals, making them vital for long-term resilience. Furthermore, improved postharvest systems encourage value addition and entrepreneurship. Farmers can move beyond selling raw produce to processing,

branding, and marketing products. For example, turning tomatoes into puree or mangoes into dried slices extends shelf life and creates new income streams. Such initiatives generate rural employment, empower women and youth, and stimulate local economies. Finally, postharvest management strengthens food security and nutrition. When less food is wasted, more reaches consumers at affordable prices. High-quality produce also retains better nutritional value, ensuring healthier diets for communities. This link between postharvest practices and nutrition is often overlooked but is critical for building strong, healthy societies.

MANGROVES OF ANDAMAN: GUARDIANS OF THE COAST AND CRADLES OF BIODIVERSITY

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Abstract

Mangroves are distinctive coastal woods that are vital to the biological and socioeconomic landscape of the Andaman and Nicobar Islands. High levels of biodiversity, including fish, crabs, birds, reptiles, and rare plant species, are supported by these ecosystems, which flourish in saline, intertidal zones. Mangroves support fisheries and local livelihoods by acting as natural barriers against storms, tsunamis, and coastal erosion. They also serve as nurseries for commercially significant marine species. In addition to their economic and ecological roles, they are essential carbon sinks that help mitigate climate change by storing "blue carbon." Despite their significance, Andaman mangroves are threatened by a number of factors, including pollution, aquaculture, coastal development, deforestation, and the effects of climate change. Afforestation, protected areas, and community-based management are examples of conservation efforts that are essential to maintaining these ecosystems. By preserving Andaman's mangroves, island populations can benefit from climate resiliency, sustainable fisheries, and biodiversity conservation.

Key Words: Mangroves, Andaman Islands, Biodiversity, Fisheries, Coastal Protection, Climate Change, Conservation

Introduction

The Andaman and Nicobar Islands, a gem of India located in the Bay of Bengal, are well known for their rich natural history, which combines immaculate coasts with deep woods. Mangroves, which form a protective green belt along the coasts, are among the most important and distinctive of these ecosystems. With unique root systems that anchor them in shifting sands and enable them to endure high tides, hurricanes, and cyclones, mangroves are amazing coastal forests that flourish in saline and tidal environments. In addition to being beautiful, these forests in the Andaman Islands are essential for maintaining natural balance and sustaining human livelihoods. Numerous mangrove species, including as *Rhizophora*, *Avicennia*, *Bruguiera*, and *Ceriops*, are found on the islands. Together, these species produce intricate habitats for innumerable species through dense networks of roots, branches, and leaves. In order to maintain marine biodiversity, these habitats serve as nurseries for fish, prawns, crabs, and mollusks. Mangroves are hotspots of ecological diversity because they provide food, shelter, and breeding grounds for birds, reptiles, and even some mammals. Mangroves offer us priceless services that go beyond their ecological importance. They serve as natural barriers against climate extremes, shielding coastal settlements from erosion, storm surges, and tsunamis. They are known as "blue carbon" ecosystems because of their capacity to store significant amounts of carbon in soil and biomass, which also helps to mitigate climate change. Despite its significance, human activities like pollution, urbanization, and the growth of aquaculture pose a threat to Andaman's mangroves. Promoting sustainable management and conservation initiatives requires an understanding of their ecological, economic, and cultural significance.

Biodiversity and Ecological Importance

The Andaman Islands' mangroves, which sustain an astounding variety of life, are among India's most ecologically vital coastal ecosystems. With specialized species that are suited to salty water, varying tides, and anaerobic soils, these forests flourish in the intertidal zones where land and sea converge. *Rhizophora mucronata*, *Avicennia officinalis*, *Bruguiera gymnorrhiza*, *Ceriops tagal*, and *Sonneratia alba* are the predominant mangrove species in the area, all of which contribute to a complex structural habitat. In addition to stabilizing the beach, their complex root systems provide microhabitats for a diverse range of creatures. Mangroves are essential marine life nurseries. Mangrove roots provide cover and an abundance of food for juvenile stages of commercially and ecologically significant species, including groupers, snappers, mud crabs, shrimp, and mollusks. Mangroves are therefore essential to maintaining the island's fisheries, which are a major source of income for the locals. A wide variety of birds, including migratory and resident species like herons, egrets, kingfishers, ospreys, and the uncommon Andaman teal, can be found in the woodlands. Mangrove regions are home to a variety of snakes, water monitors, and reptiles like the saltwater crocodile (*Crocodylus porosus*), as well as small mammals like otters and fishing cats. The ecological diversity of these forests is further enhanced by amphibians and invertebrates like mudskippers, crabs, and mollusks. Mangroves serve vital ecological roles in addition to providing habitat. By capturing sediments, heavy metals, and other contaminants before they enter the open ocean, they serve as organic biofilters that preserve water quality and sustain neighboring coral reefs. Their extensive root systems lessen the harm to human populations by shielding the coast from erosion, storm surges, and tsunamis. Furthermore, mangroves are acknowledged as important carbon sinks that store "blue carbon" in sediment and biomass, which is essential for reducing the effects of climate change. They are essential to the general health of ecosystems since they also help with soil formation, nutrient cycling, and microclimate regulation. Mangroves in the Andaman Islands are vital to human well-being, biodiversity, and coastal resiliency in ways that go well beyond their obvious greens. In addition to supporting fisheries, safeguarding populations, and preserving the delicate balance of the islands' distinctive coastal ecosystems, the conservation of these woods guarantees the survival of many species.

Role in Fisheries and Livelihoods

Mangroves are much more than just coastal woods; they are the Andaman and Nicobar Islands' economic lifelines, closely linked to the region's fisheries and the welfare of the indigenous populace. Many commercially significant marine species use these environments as natural nurseries and breeding sites. 253 fish species, as well as a variety of crustaceans, arthropods, and birds that rely on the mangrove habitat for at least a portion of their life cycle, were identified in a thorough study of mangrove ecosystems in the Andaman and Nicobar Islands. Mangrove ecosystems are crucial for maintaining local fish stocks, as evidenced by the fact that about 67–68% of these fish species are commercially significant (Kathiresan & Rajendran, 2005). Mangrove-associated species are thought to make up between 23 and 34 percent of all marine fish caught in areas where they are found, according to estimates from scientific studies conducted throughout India (Gopal & Chauhan, 2006). In addition to providing food security for coastal communities, this connection has an economic value of hundreds of millions of rupees when measured per acre and totaled throughout India's coastline. Small-scale and artisanal fishing continues to be a major source of income for many Andaman fishermen. Before entering open waters, the juveniles of commercially significant species including groupers, snappers, prawns, and crabs seek refuge in the

complex root systems of mangroves. This natural process increases fishery output without the need for artificial breeding operations. Therefore, mangrove-linked fisheries offer stable employment, particularly in remote and island areas with few other sources of income (Kathiresan, 2015). Mangroves provide related vocations in addition to direct fishing, such as crab and prawn harvesting, honey gathering, handicrafts, and even ecotourism activities like sustainable boat excursions and bird watching.

Threats and Conservation

Mangroves in the Andaman and Nicobar Islands confront numerous dangers that threaten their survival despite its ecological and socioeconomic significance. Human activity, such as land reclamation, urban growth, and coastal development, is one of the main hazards. Mangrove regions are frequently directly cleared as a result of increased tourism infrastructure and construction along shorelines, which reduces their extent and fragments habitats. Large portions of mangrove forests have also been turned into ponds by aquaculture and shrimp farming, especially near populated areas, which disturbs biodiversity and natural ecosystems (Gopal & Chauhan, 2006). Another serious threat is pollution. The health of mangrove species is impacted by the discharge of plastic debris, oil spills, and household sewage into coastal seas, which degrades water quality. These ecosystems are further stressed by the overharvesting of mangrove wood for fuel, feed, and lumber, which increases their susceptibility to natural disasters. Mangrove development, reproduction, and species composition are all impacted by climate change, which also presents a significant issue due to rising sea levels, greater cyclonic activity, and temperature changes (Kathiresan & Rajendran, 2005). The Andaman Islands have adopted a number of conservation measures in response to these challenges. To preserve mangrove ecology, the government and environmental groups have created wildlife sanctuaries and protected areas, including portions of the North Andaman and Ritchie's Archipelago. Programs for regeneration and afforestation, which sometimes involve local populations in planting and monitoring activities, seek to restore damaged mangrove regions. Because locals rely on mangroves for their livelihoods and are driven to conserve them, community participation has been very successful (Kathiresan, 2015). Furthermore, research programs that highlight the importance of mangroves for fisheries, coastal protection, and climate mitigation have supported ecotourism, environmental education, and awareness campaigns. In order to highlight the importance of mangrove ecosystems as "blue carbon" ecosystems and offer financial incentives for conservation, creative strategies like mangrove carbon credit programs are being investigated. Andaman's mangroves can be preserved for future generations by combining scientific management, community involvement, and policy actions. By preserving these woods, livelihoods are supported, ecological stability is ensured, and resistance to environmental change is strengthened.

Conclusion

The Andaman and Nicobar Islands' mangroves are remarkable coastal ecosystems that are essential to biodiversity support, ecological equilibrium, and human livelihoods. In addition to being as nurseries for a variety of commercially significant fish, crustaceans, and other aquatic species, they also operate as natural barriers, shielding shorelines from erosion, storm surges, and the effects of climate change. Mangroves are essential to the socioeconomic fabric of the islands because, in addition to their biological roles, they support local economies through fisheries, crab and prawn harvesting, honey gathering, ecotourism, and other community-based activities. Despite their significance, Andaman mangroves are threatened by a number of factors, such as pollution,

aquaculture, coastal development, deforestation, and climate change. The preservation of these ecosystems depends on conservation activities such protected areas, community-based restoration programs, environmental education, and sustainable management initiatives. The ecological and economic advantages of mangroves can be preserved for future generations by combining scientific understanding, legislative initiatives, and engaged community involvement. Mangrove survival in the Andaman Islands ultimately depends on the welfare of both humans and the natural world. The long-term prosperity of island populations, climate resilience, healthy fisheries, and biodiversity conservation all depend on protecting these green coastal guardians.

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MECHANICAL BEHAVIOR OF WOOD AND WOOD-BASED COMPOSITES: AN INTERPRETATIVE REVIEW

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Abstract

Wood and wood-based composites are increasingly used in engineering and construction as interest grows in sustainable and low-carbon materials. Despite their long history of use, these materials are often misunderstood because their mechanical behaviour differs significantly from that of conventional engineering materials. Wood responds to load in a direction-dependent and time-dependent manner and is highly sensitive to changes in moisture. This review discusses the mechanical behaviour of solid wood and engineered wood composites by linking material structure to elastic response, strength, long-term deformation, moisture interaction, and failure mechanisms. Particular attention is given to how engineered wood products are designed to reduce natural variability and improve mechanical reliability. A clear understanding of these mechanisms is essential for safe structural design and the continued development of wood as a modern engineering material.

Keywords: Wood mechanics, Engineered wood composites, Mechanical behaviour, Anisotropy, Viscoelasticity, Creep, Moisture effects, Structural performance, Sustainable materials, Timber engineering

Introduction

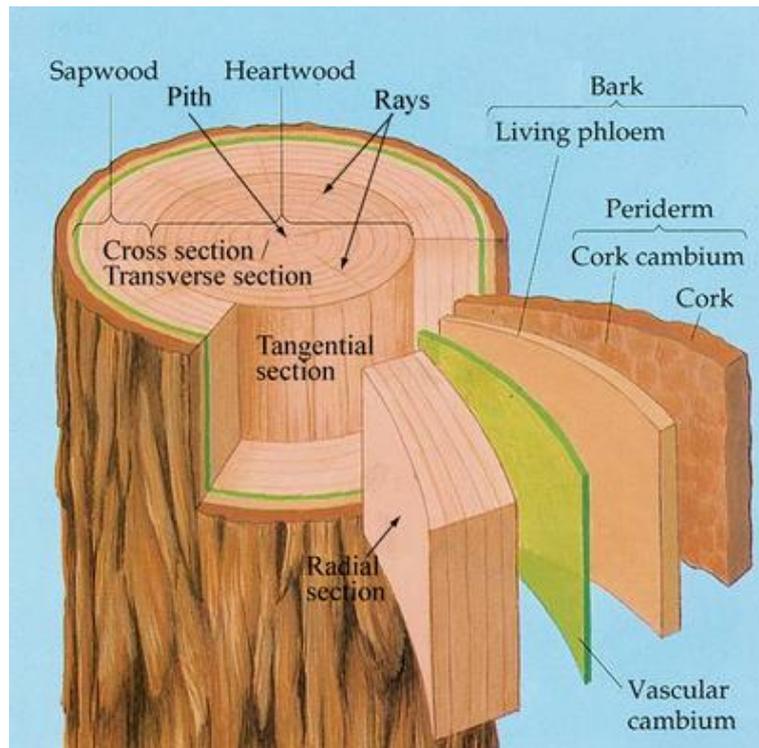
Wood has been used as a construction material for centuries, yet its importance has increased rather than diminished in recent decades. Growing pressure to reduce carbon emissions and reliance on energy-intensive materials has led engineers to reconsider wood as a primary structural material. Compared with steel and concrete, wood requires less energy to produce and stores carbon throughout its service life, making it an attractive option from an environmental perspective (Forest Products Laboratory, 2010).

At the same time, wood presents challenges that are not commonly encountered with more uniform materials. Its properties vary with direction, moisture content, and duration of loading, which can make mechanical behaviour difficult to predict. Engineered wood products such as plywood, laminated veneer lumber (LVL), and oriented strand board (OSB) have been developed to address these limitations. This article reviews the mechanical behaviour of wood and wood composites in a way that connects fundamental material characteristics with practical engineering performance.

Wood Structure and Directional Effects

From a materials perspective, wood can be understood as a natural composite. It consists mainly of cellulose fibers embedded within a matrix of lignin and hemicellulose. The cellulose fibers are responsible for most of the tensile strength, while lignin provides stiffness and resistance to

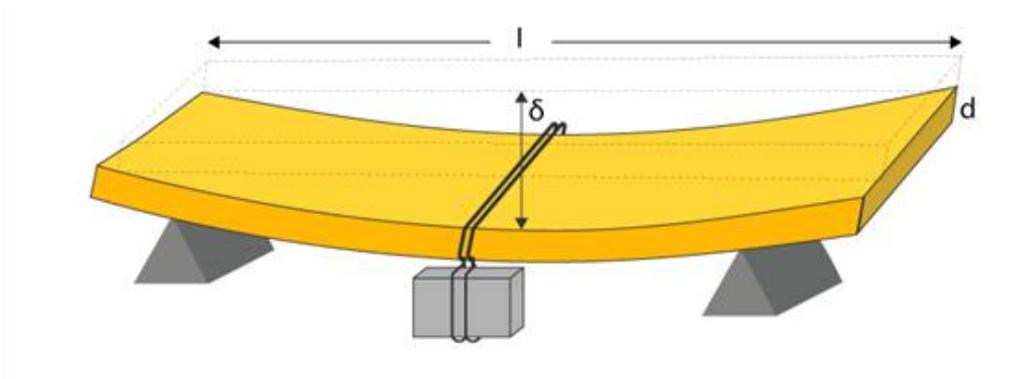
compression (Gibson & Ashby, 1997). This combination results in a lightweight but mechanically efficient material. A key feature of wood is that its internal structure is strongly aligned, leading to pronounced directional behaviour. Wood is therefore treated as an orthotropic material, with different properties along the longitudinal, radial, and tangential directions. Mechanical performance is highest along the grain, where fibers are aligned with the applied load. Across the grain, properties are significantly lower because deformation is controlled by weaker bonding between cells and growth ring features (Bodig & Jayne, 1982).



Structure of wood (source- [Wood Anatomy - Search Images](#))

Elastic Behavior

Under small loads, wood behaves elastically and will largely return to its original shape once the load is removed. However, stiffness varies considerably with direction. The modulus of elasticity parallel to the grain is typically much higher than in the radial or tangential directions, often by several times (Dinwoodie, 2000).



Elastic Behavior of wood(Source- [Elastic Behavior - Search Images](#))

Moisture content further complicates elastic response. As wood absorbs moisture, it becomes more compliant and less stiff. This effect is especially pronounced below the fiber saturation point, where relatively small changes in moisture content can produce noticeable changes in stiffness (Forest Products Laboratory, 2010).

Strength and Failure Characteristics

The strength of wood depends strongly on how the load is applied. When stressed parallel to the grain, wood shows relatively high strength in both tension and compression due to efficient load transfer through the aligned fibers. In contrast, tensile loading perpendicular to the grain often results in sudden failure, as it relies on weak bonding between cells rather than fiber strength (Bodig & Jayne, 1982). Compression parallel to the grain typically produces gradual failure through cell wall buckling rather than abrupt fracture. In bending, failure usually initiates in the tensile zone, while the compressive side undergoes progressive crushing. Shear strength is comparatively low and frequently controls failure in beams and connections (Dinwoodie, 2000).

Time-Dependent Behaviour

One of the most distinctive features of wood is its tendency to deform over time when subjected to sustained loading. This phenomenon, known as creep, can lead to deflections that continue to increase long after construction. Creep behaviour is influenced by stress level, temperature, and moisture conditions (Hunt, 1999).

Effects of Moisture on Mechanical Performance

Moisture has a significant influence on nearly all mechanical properties of wood. Increasing moisture content generally reduces strength and stiffness while increasing deformation. Below the fiber saturation point, moisture changes also cause swelling and shrinkage that differ by direction (Forest Products Laboratory, 2010).

Engineered Wood Composites

Engineered wood composites were developed to improve the predictability and reliability of wood-based materials. Plywood uses cross-laminated veneers to improve dimensional stability, while LVL and OSB align wood elements to maximize strength and stiffness (Bodig & Jayne, 1982).

Composite Wood Types – Simple Study Table

Type	Made From	Key Features	Common Uses
Plywood	Thin wood veneers glued in layers	Strong, stable, resists warping	Furniture, doors, flooring, construction
MDF (Medium-Density Fiberboard)	Fine wood fibers + resin	Smooth surface, easy to paint	Cabinets, furniture, wall panels
Particle Board	Wood chips & sawdust + resin	Cheap, lightweight, weak to moisture	Low-cost furniture, shelves
OSB (Oriented Strand Board)	Large wood strands arranged in layers	Strong, economical	Walls, roofs, subfloors
Hardboard (HDF)	Highly compressed wood fibers	Dense, smooth, thin	Furniture backs, doors, flooring core
Blockboard	Softwood strips with veneer faces	Light, good screw holding	Tables, doors, partitions

Type	Made From	Key Features	Common Uses
LVL (Laminated Veneer Lumber)	Veneers glued in same direction	Very strong, uniform	Beams, headers, framing
WPC (Wood-Plastic Composite)	Wood fibers + plastic	Water-resistant, durable	Decking, outdoor furniture



Types of Composite Wood

(Source- [Composite Wood Types. The Differences and Uses Explained.](#))

Conclusions

Wood is a naturally complex and anisotropic material whose mechanical behavior is strongly influenced by its cellular structure and environmental factors such as moisture and temperature. Solid wood exhibits excellent strength and stiffness along the grain, but its performance can vary due to natural defects, knots, and dimensional instability. Engineered wood composites address these limitations by reorganizing wood fibers, particles, or veneers into more uniform products. These composites provide improved consistency, better dimensional stability, and greater design flexibility. Consequently, engineered wood plays a vital role in modern construction and furniture manufacturing while promoting efficient and sustainable use of timber resources.

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MICROBES AS DEFENSIVE AGENTS AGAINST ROOT-KNOT NEMATODES (RKN)

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Introduction

The microscopic roundworms known as root-knot nematodes are members of the genus *Meloidogyne* and live in the soil. They severely damage a variety of crops, including fruits, vegetables, ornamentals, and field crops (Sahebani and Hadavi, 2008). They are among the most economically significant plant-parasitic nematodes in the world. As a result of these nematodes infecting plant roots, distinctive swellings or galls occur on the root system, thus the term "root-knot." The plant's capacity to absorb water and nutrients is hampered by these galls, which interfere with the roots' regular function and cause stunted growth, withering, and yield loss. Severe infestations have the potential to kill plants. The life cycle of a root-knot nematode is intricate and consists of eggs, juveniles, and adults. They may live for long periods of time in soil and have a broad host range, making them challenging to control once established. Various control strategies such as cultural practices, chemical control, and biological control were used for the management of RKN population.

Cultural practices include crop rotation, the use of resistant cultivars, soil solarization, and the application of nematicides are among the management measures for root-knot nematodes. Incorporating biological management techniques into a comprehensive pest management programme can effectively reduce nematodes and is frequently a more environmentally friendly and sustainable alternative to chemical control measures. Biological control involves the use of mostly antagonistic fungi and bacteria mainly PGPR (Ashraf and Khan, 2010). Plant growth promoting rhizobacteria are bacteria that live in the "rhizosphere" of a plant's roots and promote plant regulators and boost nutrient availability (PGPR).

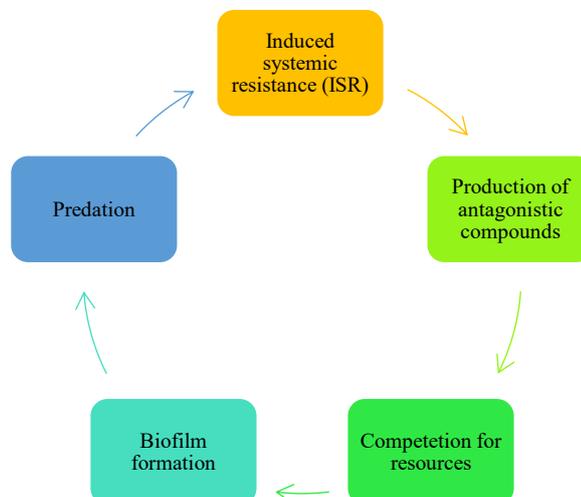


Fig. 1. Mechanism of biological control agents against RKN

Mode of action of microbes as defensive agents against RKN

Induced systemic resistance, or ISR: It is the ability of some advantageous microorganisms to make plants resistant to nematodes. These microorganisms invade the rhizosphere of the plant and cause a systemic reaction that strengthens the plant's defences against nematode infestation. This may involve the synthesis of antimicrobial substances, the reinforcement of cell walls, and the stimulation of genes linked to defence (Sharma et al., 2024).

Production of Antagonistic Compounds: Microbes in the rhizosphere have the ability to produce antimicrobial compounds and secondary metabolites that stop nematodes from growing and reproducing. These substances can reduce the number of nematodes in the soil and lessen harm to plant roots by directly targeting nematodes, interfering with their growth, preventing egg hatching, or disrupting their life cycle. Antibiotics, enzymes, and volatile organic compounds (VOCs) produced by specific bacteria, fungi, and actinomycetes are a few examples of these substances.

Competition for Resources: In the rhizosphere, microbes and nematodes fight for vital resources including oxygen, space, and nutrients. Beneficial microorganisms can suppress nematode population growth and decrease their capacity to feed on plant roots by outcompeting nematodes for these resources.

Biofilm Formation: In the rhizosphere, certain microorganisms produce biofilms that act as a physical barrier, hindering the movement of nematodes in the soil and preventing them from reaching plant roots. Moreover, biofilms can support advantageous bacteria that generate antimicrobial substances, strengthening the plant's resistance against nematodes.

Predation: By feeding on root-knot nematodes, predatory microbes like nematophagous fungi and predatory nematodes can lower the number of nematodes in the soil. Through a variety of tactics, including as trapping, penetration, and ingestion, these predators target nematodes, eventually resulting in nematode mortality. Numerous microorganisms have been investigated and employed in agricultural contexts to control root-knot nematodes (Khan *et al.*, 2023):

***Paecilomyces lilacinus*:** This fungus is known for its ability to parasitize and kill nematodes, including root-knot nematodes. It infects nematodes by penetrating their cuticle and consuming their contents. *Paecilomyces lilacinus* has been formulated into commercial biopesticides for nematode control.

***Bacillus thuringiensis* (Bt):** While primarily known for its effectiveness against insect pests, certain strains of Bt have demonstrated nematicidal activity against root-knot nematodes. Bt produces crystal proteins (Cry proteins) that are toxic to nematodes upon ingestion.

***Pseudomonas* spp.:** These bacteria can colonize the rhizosphere and suppress nematode populations through direct antagonism or by inducing systemic resistance in plants.

***Arthrobotrys* spp.:** These nematophagous fungi are capable of trapping and parasitizing nematodes, including root-knot nematodes. They produce adhesive structures such as constricting rings or adhesive networks that ensnare nematodes, leading to their death and subsequent nutrient uptake by the fungus.

***Pasteuria penetrans*:** This bacterium is an obligate parasite of root-knot nematodes and has been studied as a potential biological control agent. *Pasteuria penetrans* infects nematodes through spore attachment and subsequently inhibits nematode reproduction, reducing nematode populations in the soil.

Trichoderma spp.: Certain species of *Trichoderma* fungi have been investigated for their potential to control root-knot nematodes. These fungi produce enzymes and secondary metabolites that can degrade nematode cuticles or inhibit nematode development and reproduction.

Nematophagous nematodes: Some predatory nematodes, such as members of the genera *Steinernema* and *Heterorhabditis*, are used as biological control agents against root-knot nematodes. These nematodes infect nematode larvae with symbiotic bacteria, leading to nematode death within a few days.

Conclusion

Different microbial agents, or combinations of them, may be more effective in controlling nematode populations depending on parameters like soil type, crop variety, and environmental circumstances. Prior research on the control of nematodes has revealed that the overuse of numerous chemicals have contaminated the land, water, and environment. They have also had an impact on human health. Consequently, taking into account each of these issues, microbial bio-control became evident as a strong alternative to chemicals. Numerous microorganisms, including bacteria and fungus, exhibit strong nematicidal activity. Fungi have a variety of ways to fight nematodes, including rhizospheric colonisation, inducing resistance in plants, and breaking down and absorbing the nematodes cuticle and allowing for penetration. On the other hand, bacteria counteract the parasitism of RKNs by producing toxic substances known as antibiotics, competing with nematodes in the rhizosphere, producing many lytic enzymes such as lipases, chitinases, collagenases, and proteases, and causing systemic resistance. In addition to bio-control methods, bacteria and fungi increase the intake of nutrients (N and P) from the soil and nitrogen fixation, which in turn promotes plant development and production.

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MICROPLASTICS AND AQUACULTURE: THE INVISIBLE THREAT TO OUR BLUE ECONOMY

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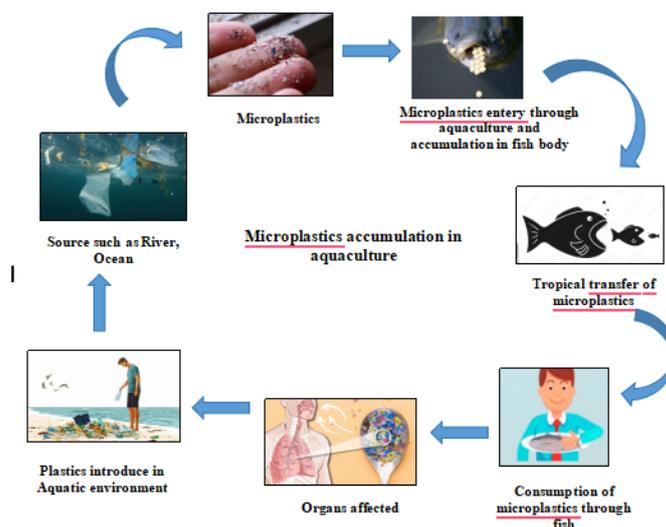
Abstract

Microplastics (< 5mm) have become a growing concern in aquaculture due to their persistence and toxic impacts on aquatic organisms and human health. This study highlight the major source of microplastics from river, marine environment and aquatic operations include fishing gear, feed ingredients and packing material. Experimental reveals that microplastics such as PVC, PET and polystyrene cause oxidative stress, tissue damage, reduce growth, reproduction and fecundity rate in fish. Bioaccumulation through the food chain creates potential risk to human organs including liver, kidney and brain. The study emphasizes mitigation measures such as microbial degradation, mangrove filtration and biodegradable fishing gear. These findings underline the urgent need for stringent regulations and sustainable management to protect the aquaculture production and food safety.

Introduction

Microplastics are synthetic or polymeric particles with regular or irregular shapes (Frias and Nash, 2019), which refer the plastics smaller than 5mm in size (Arthur *et al.*, 2009). Aquaculture is fast growing food sector and global demand in market. It act as good source of protein for human consumption. The microplastic accumulation in large number of aquaculture environment create problems eg: the PVC material affect the decomposition result acidic water. Microplastics and microplastic-related activities affect the immune system of fish and produce neurotoxicity, it reduce the quality of aquaculture products. Based on the adverse effects of microplastics control measures against emerging pollutant include fishing gears, plastic packing bag. The government legislation on the detection process and limit value of microplastics in aquaculture is also an urgent direction (Lam *et al.*, 2018). Clear provisions help to reduce microplastics in aquaculture and ensure the food safety.

Microplastic from external environment



- **River** : The source of river include Industrial effluents, human activities, sewage treatment plants and agriculture activity 1.2×10^5 tons of plastics are produced annually in the Ganges River basin. Multiple studies have demonstrated that microplastic pollution of aquaculture areas in estuaries and coastal areas near estuaries is associated with high abundance of microplastics in local rivers (Ma *et al.*, 2020). Therefore, rivers as an important source of microplastic pollution in aquaculture.
- **Marine** : Marine microplastics pollution create serious threat to marine aquaculture and marine ecosystem. According to statistics, 4.8-12.7 million metric tons of plastic waste enter from land to marine in 2010 (Jambeck *et al.*, 2015), river load 1.15-2.41million metric tons per year. The source include coastal community, tourism, leisure, commercial fishing, shipping and marine industry.

Microplastics produce during aquaculture

- **Fishing gears** : Fishing gear used in aquaculture introduce microplastics due to long term immersion, erosion, wear, collision, nets, fishing ropes, floating balls, cage culture and raft generate microplastics (Food and Nations, 2018).

A coastal marine study in China shows microplastics in mariculture 11.49 particles/m, much higher than that in other areas without mariculture.

- **Wild caught Aquatic animals** : fish and shrimp if affected by microplastic pollution are used as fish meal and shrimp meal in feed ingredients introduce microplastics into aquaculture environment. In Italy 50–100mg/kg of polystyrene, 50–100mg/kg of highly oxidized polyolefins and 12.9mg/kg of polyester had been found in fish meal (Castelvetro *et al.*, 2021).
- **Packing material** : It is very common in aquaculture industry through polystyrene boxes, corrugated plastic boxes and plastic trays. Study shows Polystyrene packaging also found microplastics pollution.

Aquaculture products accumulate microplastics through the digestive system, gill and skin (Moore *et al.*, 1998). Therefore, the abundance of microplastics in aquaculture products is generally higher than that in wild aquaculture products.

Microplastics effect on Aquaculture

Microplastics found in fish, shrimp, mussel, oyster and crabs. Microplastics create toxic effects such as oxidative stress in aquaculture organisms, change in behaviour, growth and reproduction. It affect fish metabolism such as lipid, carbohydrate metabolism, oxidative stress and toxin excretion it affect the immune response.

- **Oxidative stress** : The large production of ROS affect the cholesterol level and enzyme activity related to lipid metabolism in fish.

Case study: PVC and PET microplastics with the sizes of 40–150µm can cause oxidative damage to the cells of sea bream and sea bass (Espinosa *et al.*, 2019).

Oxidative stress in zebrafish, which can lead to the decrease of heart rate in zebrafish (Pitt *et al.*, 2018).

- **Brain function** : microplastic particle of 24nm and 27nm can affect the development of fish brain. It slow down the brain and acetylcholinesterase activity.
- **Heart and gill function** : The effect of microplastics can reduce heart and gills functions.

Case study: oxidative stress in zebrafish, which can lead to the decrease of heart rate in zebrafish (Pitt *et al.*, 2018)

Clarias gariepinus affected by microplastics with 60 µm cause tissue damage in the gills.

➤ **Behavior, growth and reproduction** : Microplastics introduced by aquatic organisms cause gastrointestinal problem result decrease digestive system of fish.

Case study: Microplastics can reduce the feeding and swimming abilities of *Sebastes schlegelii* (Yin *et al.*, 2018).

Effect of microplastics on human health

Microplastics could transfer between trophic levels from herbivores to carnivores, which mean accumulation in food chain. Microplastics affected aquatic product affect the human health. It mixed with blood and circulate through various organs through blood. It enter into lungs cause lung inflammation, cerebral softening in brain, thoracic lymph nodes through macrophage affect liver, kidney, spleen and immune response.

Current measures to reduce microplastic pollution in aquaculture

The treatment methods of microplastic pollution, such as membrane bioreactors, electro-coagulation and zirconium metal-organic framework-based foam material filtration process for seawater. It reduce 95% of microplastics enter into environment. Mangroves are aquatic flora reduce pollutant in water and soil(Liu *et al.*, 2022). *Bacillus* sp. and *Rhodococcus* sp. microorganisms degrade the microplastics (Auta *et al.* 2018). Replacing plastic fishing gear to biodegradable material for fishing (Deroine *et al.*, 2019).

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NANO-FERTILIZERS: SMALL PARTICLES, BIG SAVINGS FOR FARMERS

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Abstract

Growing input prices, deteriorating soil fertility, and the need to feed an expanding population provide challenges for modern agriculture. Large amounts of applied nutrients are lost to the environment, and conventional fertilizers frequently fall short. Presenting nano-fertilizers, which are little particles with enormous potential. Nano-fertilizers can increase productivity, lower input costs, and promote sustainable farming by precisely delivering nutrients where and when crops need them. This article examines their science, advantages, real-world applications, and potential to revolutionize agriculture globally.

Keywords: Nano-fertilizers, Nutrient use efficiency, Precision agriculture, Sustainable farming, Soil fertility, Crop productivity

Introduction

Farmers have been using traditional fertilizers to feed their crops for decades. However, many fields exhibit uneven growth, inadequate fertilizer absorption, and occasionally unsatisfactory results despite extensive use. Why? Over half of the fertilizer can be wasted because to nutrient losses via leaching, volatilization, or fixing. In addition, soils are gradually losing their inherent fertility as fertilizer costs continue to rise.

Nano-fertilizers are useful in this situation. Consider them "smart fertilizers," which are both small enough to be effectively absorbed and potent enough to provide crops with precisely what they require. Although they are not a panacea, they do provide a more intelligent method of fertilization, particularly when used carefully in conjunction with traditional methods.

What Are Nano-Fertilizers?

Nano-fertilizers are essentially nutrients in ultra-small particles, often less than 100 nanometers so tiny that millions could fit on the tip of a pin. Their small size gives them a large surface area, which makes them more reactive and easier for plants to absorb. Unlike traditional fertilizers that can sit in the soil and get lost, nano-fertilizers release nutrients gradually, in sync with crop needs.

Imagine giving your plants exactly the right amount of food at the right time, instead of dumping a whole bag into the soil and hoping for the best. That's the essence of nano-fertilizers.

How They Operate

The basic idea behind how nano-fertilizers function is efficiency by accuracy. They can infiltrate leaves through microscopic apertures known as stomata. Their tiny size makes it easier for them to go to roots in the soil. The outcome? With fewer trash, plants receive more nutrients.

This "slow and steady" distribution lowers the quantity of fertilizer a farmer must use, promotes uniform crop growth, and promptly corrects deficiencies. It's better for the environment and the pocketbook in addition to yields.

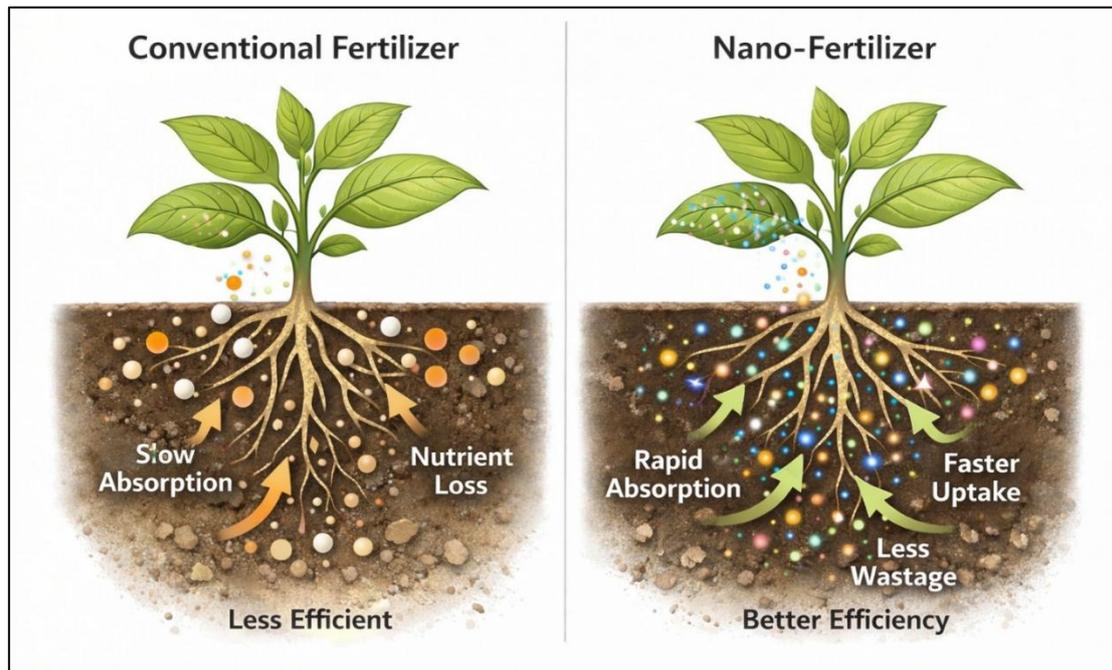


Figure 1. Comparison of Nutrient Absorption in Plants Using Conventional and Nano-Fertilizers

Nano-Fertilizer Types

Depending on the nutrients they supply and how they release them, there are several varieties of nano-fertilizers. Farmers may select the best product for their crops by being aware of these types:

Macronutrient Nano-Fertilizers : These fertilizers provide the main nutrients that plants require in greater quantities, including potassium (K), phosphorus (P), and nitrogen (N). Nitrogen provides plants a bright green hue and encourages the development of luxuriant leaves. Phosphorus promotes early development, fortifies roots, and facilitates blooming. Potassium supports the general health of plants, increases disease resistance, and improves fruit quality. Compared to conventional fertilizers, these fertilizers' nano-size makes it possible for roots and leaves to absorb nutrients more effectively, resulting in improved growth and increased yields.

Micronutrient Nano-Fertilizers: Micronutrient nano-fertilizers supply vital trace elements such as zinc (Zn), iron (Fe), copper (Cu), and boron (B), which are needed in trace amounts yet are vital to plant growth. While avoiding common deficiency issues including yellowing leaves, weak stems, and poor fruit quality, these nutrients promote blooming, fruit set, and seed development. These fertilizers are quite efficient even when administered in little amounts because of their nanoscale, which makes them more soluble and absorbed more quickly.

Nano-Coated or Encapsulated Fertilizers: These fertilizers are made to release nutrients gradually over time in accordance with the needs of the plant. This slow-release characteristic lowers the number of treatments required and minimizes nutrient losses from leaching, runoff, or volatilization. These fertilizers increase nutrient efficiency, save labor and expenses, and produce healthier and more productive crops by delivering a consistent supply of nutrients.

Liquid Nano-Fertilizers: Liquid nano-fertilizer formulations are simple to combine with water and use as irrigation systems or foliar sprays. They facilitate quicker absorption of nutrients, and their benefits are frequently apparent quickly. Liquid nano-fertilizers provide consistent administration throughout the crop, guaranteeing that every plant gets enough nutrients. They are particularly helpful for greenhouses, high-value crops, and circumstances requiring prompt treatment of nutrient shortages.

The Importance of Nano-Fertilizers for Farmers

For farmers, nano-fertilizers provide a number of concrete advantages. By distributing nutrients more effectively, they lower fertilizer costs by enabling less amounts to produce similar or greater yields. Plants react to deficiencies more quickly, which promotes healthy development and lowers the chance of produce loss. Higher-quality crops, such as better grains, fruits, or vegetables, are frequently produced with nanofertilizers. They also contribute to environmental protection by reducing greenhouse gas emissions and fertilizer runoff. However, when utilized as a component of an integrated nutrition management system rather than as a stand-alone remedy, their efficacy is enhanced.

Practical Application Tips

To get the best results from nano-fertilizers, farmers should follow a few simple guidelines. Apply them at critical crop stages, such as vegetative growth or flowering, to ensure maximum nutrient uptake. Use proper dilution and clean water when spraying, and apply during cooler hours, like early morning or evening, to prevent evaporation or leaf burn. Always follow the label instructions and avoid overdosing. These simple precautions can significantly improve efficiency, plant health, and overall crop performance.

Combining Conventional Fertilizers

The best use for nano-fertilizers is as an addition to traditional fertilizers, not as a substitute. By integrating them, basal fertilizer dosages can be partially reduced, usually by 25–50%, without sacrificing yield. This combination promotes soil fertility, lowers input costs, increases nutrient efficiency, and guarantees a balanced supply of nutrients. Large-scale agricultural systems, precision agriculture, and areas subject to environmental fertilizer usage rules all benefit greatly from this kind of integration.

Examples from the Real World

The practical advantages of nano-fertilizers have been proven by field tests conducted all over the world, from Brazil and Europe to China and India. Yields in cereal crops, such as wheat and rice, rose by 5–10% while utilizing less urea, which decreased expenses and the impact on the environment. In horticultural crops, nano-fertilizers prevented micronutrient deficits and promoted healthier plant development; in vegetables, they hastened fruit set and enhanced quality. In a single season, farmers who properly use these technologies frequently see considerable gains in crop health and production, which promotes broader adoption and shows the potential for high-efficiency, sustainable farming around the globe.

Benefits to the Economy and Environment

By decreasing the amount of fertilizer needed, cutting labor and input costs, and raising farmers' net profit, nano-fertilizers offer definite financial benefits. Their effective fertilizer delivery lowers greenhouse gas emissions, eliminates losses into water bodies, and lessens soil contamination, all of which support climate-smart and sustainable agricultural practices globally.

Challenges and possibilities for the Future

Despite its potential, there are obstacles that may prevent nano-fertilizers from being widely used. These include a lack of uniform norms in many areas, increased upfront expenses, and low farmer knowledge. However, these problems are increasingly being addressed by continuing research, legislative assistance, and farmer training initiatives. Future developments including crop-specific formulations, slow-release smart fertilizers, and integration with precision farming technology are expected to establish nano-fertilizers as a common agricultural tool worldwide.

Conclusion

An inventive and useful strategy for contemporary, sustainable farming is the use of nano-fertilizers. When applied properly, they improve crop quality, lower input costs, increase nutrient efficiency, and save the environment. They are a potent supplement to help farmers grow more with less, promoting both profitability and sustainability globally, even though they are not a replacement for sound soil and crop management techniques.

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REDUCING WASTAGE THROUGH POSTHARVEST VALUE-ADDING TECHNOLOGIES

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Abstract

Postharvest wastage of fruits and vegetables is one of the most serious challenges in Indian agriculture, with losses estimated at 20–40%, and even higher for highly perishable commodities. These losses occur due to poor handling, lack of storage, market gluts, and limited processing facilities. Postharvest value addition technologies offer an effective solution to reduce wastage, improve shelf life, stabilise prices, and enhance farmers' income. This article discusses various postharvest value addition technologies, their principles, applications, and role in minimising wastage while linking them to market opportunities and income generation.

Introduction

India is among the world's largest producers of fruits and vegetables, owing to its diverse agro-climatic conditions and year-round production potential. Despite this production strength, a substantial share of horticultural produce is lost after harvest due to weak postharvest management systems and limited value addition. Horticultural commodities are inherently perishable because of their high moisture content, active physiological processes, and sensitivity to temperature fluctuations, relative humidity, and mechanical injury. These factors make fruits and vegetables highly vulnerable to quality deterioration, physiological disorders, and microbial spoilage during harvesting, handling, storage, transportation, and marketing.

Postharvest losses have serious economic, nutritional, and environmental implications. For farmers, losses translate into reduced marketable surplus, distress sales during peak seasons, and lower price realization. At the national level, postharvest wastage undermines food and nutritional security, wastes scarce resources such as land, water, energy, and labour invested in production, and increases greenhouse gas emissions associated with unused produce. Furthermore, inconsistent quality and limited shelf life restrict access to organized retail, processing industries, and export markets, thereby constraining the growth potential of the horticulture sector. In this context, postharvest value addition has emerged as a critical strategy to minimize wastage and enhance the efficiency of the horticultural value chain. Postharvest value addition involves a range of activities carried out after harvest that improve the form, quality, shelf life, safety, and market value of produce. These include primary operations such as cleaning, sorting, grading, packaging, and storage, as well as secondary processing techniques like drying, pulping, fermentation, and by-product utilization. Importantly, value addition enables the effective use of surplus, cosmetically inferior, or low-grade produce that is often rejected in fresh markets. By converting perishable raw produce into stable, diversified, and market-oriented products, postharvest value addition reduces losses, stabilizes prices, and enhances income opportunities for farmers. It also promotes rural

employment, women participation, and Agri-entrepreneurship, particularly through Farmer Producer Organizations (FPOs) and small-scale processing units. Moreover, strengthening postharvest value addition aligns with national priorities such as doubling farmers' income, reducing food loss and waste, promoting food processing industries, and achieving sustainable agricultural and rural development. Thus, postharvest value addition serves as a powerful tool to transform horticultural wastage into economic gain while improving the resilience and sustainability of the food system.

Understanding Postharvest Wastage

Causes of wastage

Postharvest losses stem from a variety of factors, including improper harvesting techniques, rough handling, mechanical damage during transport, physiological deterioration due to delayed cooling, microbial spoilage, lack of cold storage infrastructure, market glut leading to price crashes, and inadequate processing facilities. These issues are particularly pronounced in rural areas where infrastructure and awareness are limited.

Types of losses

Postharvest losses can be categorised into quantitative and qualitative types. Quantitative losses refer to physical reductions in produce, such as weight loss, decay, and spillage. Qualitative losses involve deterioration in appearance, nutritional value, and flavour, making the produce less appealing to consumers. Even a modest reduction in wastage—by 5 to 10 per cent—can significantly enhance national food availability and improve farmer profitability.

Concept of Postharvest Value Addition

Value addition is the process of increasing the economic worth of a commodity by altering its form, location, or timing of availability. The primary objectives of value addition include reducing perishability, extending shelf life, improving marketability, diversifying income sources, and mitigating risks associated with price fluctuations. Depending on the scale and available infrastructure, value addition can range from simple, low-cost interventions to advanced technological solutions.

1. Primary Postharvest Value-Addition Technologies

Primary value addition involves minimal processing but yields substantial benefits in reducing wastage and improving market readiness.

Cleaning and Washing

Cleaning and washing remove soil, microbes, and pesticide residues, thereby enhancing the appearance and safety of produce. This step reduces microbial spoilage and increases acceptance in organised retail markets.

Sorting and Grading

Sorting and grading involve separating produce based on size, colour, maturity, and quality. Defective items are diverted for processing, preventing the spread of decay and enabling efficient channelisation of produce to appropriate markets.

Packaging

Effective packaging using plastic crates, corrugated fibreboard boxes, and modified atmosphere packaging reduces mechanical injury, maintains freshness, and extends shelf life. Proper packaging is essential for maintaining quality during transport and storage.

Pre-cooling

Pre-cooling involves the removal of field heat through methods like hydro-cooling, forced air cooling, and ice cooling. This process slows down respiration and delays spoilage, preserving the freshness of produce.

Secondary value addition technologies

Secondary value addition entails processing and converting produce into stable, long-lasting products.

Drying and Dehydration

Drying reduces moisture content, inhibiting microbial growth. Technologies include sun drying, solar drying, hot air drying, and freeze drying. Products such as dried fruits, vegetable flakes, and powders can be stored for months, especially useful during glut seasons.

Processing into Pulp, Juice, and Puree

Fruits like mango, tomato, guava, and banana are processed into pulp, juice, and puree. This helps utilise overripe, misshapen, or market-rejected produce, reducing wastage and creating value-added products.

Fermentation technologies

Fermentation is used to produce pickles, vinegar, wine, and fermented beverages. It extends shelf life, enhances nutritional value, and opens niche markets for traditional and artisanal products.

Minimal processing and Fresh-cut produce

Minimal processing includes peeling, slicing, and preparing ready-to-cook vegetables. It requires strict hygiene, cold chain management, and proper packaging. These products cater to urban consumers seeking convenience, thereby increasing demand.

Advanced Postharvest Technologies

Advanced technologies offer sophisticated solutions for long-term storage and quality preservation.

Cold storage and Controlled atmosphere storage

Cold storage and controlled atmosphere storage slow down respiration and reduce physiological disorders. They are effectively used for crops like apples, onions, potatoes, and citrus, enabling long-term storage and off-season sales.

Edible coatings

Natural edible coatings made from chitosan, starch, aloe vera, and plant gums reduce moisture loss, delay ripening, and extend shelf life. These coatings are safe and environmentally friendly.

Use of Postharvest chemicals

Postharvest treatments such as calcium applications, fungicides, and ethylene inhibitors like 1-MCP help reduce decay and physiological disorders, maintaining the quality of produce during storage and transport.

Value addition through by-product utilization

Processing waste is a major source of postharvest wastage. By-products such as fruit peels, pomace, and seeds can be converted into valuable products. For example, fruit peels can yield pectin and essential oils, pomace can be used for dietary fibre and antioxidants, and seeds can be processed for oil extraction. Utilising by-products reduces environmental pollution, generates additional income, and promotes a circular economy.

Role of value addition in market stabilisation

During peak seasons, markets often experience a glut, leading to price crashes and unsold produce. Value addition absorbs surplus produce, stabilises supply, and prevents distress sales. Processed products have longer shelf life, can be sold during off-season, and are less susceptible to price fluctuations, thereby ensuring better price realisation for farmers.

Role of Farmer-Producer Organisations (FPOs)

FPOs play a pivotal role in promoting postharvest value addition. They establish common processing units, facilitate collective marketing, and enable branding and packaging. By accessing government schemes and pooling resources, FPOs empower farmers to produce value-added goods that fetch premium prices in the market.

Employment and Rural Entrepreneurship

Postharvest value addition creates employment opportunities in rural areas, encouraging participation from women and youth. It supports Agri-startups and enables the establishment of small-scale processing units with low investment. These initiatives contribute to rural development and economic diversification.

Government support and schemes

The government has launched various initiatives to promote postharvest value addition, including subsidies for cold chain infrastructure, support for food processing units, skill development programs, and training workshops. Proper utilisation of these schemes can significantly enhance the adoption of value-added technologies among farmers and entrepreneurs.

Case studies (Field-Level Impact)

Real-world examples highlight the effectiveness of postharvest value addition. Mango pulp units have reduced wastage by 30–40%, onion dehydration units have helped stabilise prices, and tomato processing facilities have minimised distress sales. These case studies demonstrate the tangible benefits of investing in postharvest technologies.

Challenges in adoption

Despite its benefits, the adoption of postharvest value addition faces several challenges, including a lack of awareness, high initial investment costs, limited technical skills, and inadequate market linkage. Addressing these issues through targeted training, extension services, and financial support is essential for widespread implementation.

Prospects

Emerging technologies such as smart packaging, bio-preservatives, nanotechnology, and digital market integration hold promise for further reducing wastage and improving profitability. These innovations will enhance traceability, quality assurance, and consumer trust, paving the way for a more resilient horticulture sector.

Conclusion

Postharvest value addition is a powerful strategy to reduce wastage, extend shelf life, stabilise markets, and enhance farmers' income across the horticultural value chain. Surplus and low-grade produce should no longer be perceived as waste, but rather as valuable raw material for a wide range of value-added products such as processed foods, nutraceuticals, and industrial by-products. Adoption of appropriate postharvest technologies at the farm, community, and industrial levels enables better utilisation of seasonal surpluses, reduces distress sales, and improves price realisation.

A holistic and integrated approach involving capacity building, infrastructure development, farmer collectivisation, and market linkage is essential for the successful implementation of postharvest value addition. Strengthening Farmer-Producer Organisations, promoting small-scale processing units, and encouraging rural entrepreneurship can significantly enhance income opportunities, particularly for small and marginal farmers, women, and rural youth. In addition, supportive government policies, access to credit, and technology transfer play a crucial role in accelerating adoption. By reducing postharvest losses, postharvest value addition also contributes to food and nutritional security, efficient use of natural resources, and mitigation of environmental impacts associated with food wastage. Therefore, integrating postharvest value addition into mainstream horticultural development can transform India's horticulture sector into a more resilient, competitive, and sustainable system, delivering long-term benefits to farmers, consumers, and the environment alike.

MILLETS IN INDIA: AN OVERVIEW AND WAY FORWARD

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Introduction

Transforming the food system is essential, as existing food systems are unsustainable, often infringe on natural habitats, pollute the planet, increase rural poverty, and cause ill health and disease (www.worldbank.org). Food systems account for about one-third of global anthropogenic greenhouse gas emissions (Crippa *et al.*, 2021). In India, a cereal-centric diet accounts for 50% of total water used in agricultural production (Kayatz *et al.*, 2019). The cereal-centric diet, which is low in diversity, also leads to hidden hunger (Bamji *et al.*, 2020; Ritchie *et al.*, 2018). Globally, over 2 billion people suffer from hidden hunger, with nearly half living in India (Ritchie *et al.*, 2018). Millets can help address the challenges mentioned above if cereal-based diets are diversified with millets.

Millets are not resource-intensive and are less sensitive to climate variation (Davis *et al.*, 2019), and their global warming potential is lower than that of major cereals like rice, wheat, and maize (Saxena *et al.*, 2018). Millets are rich in protein, fiber, and micronutrients. They are gluten-free and have a low glycaemic index, which helps combat malnutrition, cardiovascular disease, digestive problems, celiac disease, and diabetes. Millets also contain minerals, vitamins, and antioxidants that help detoxify the human body (Saini *et al.*, 2021). Millets are cultivated for food, feed, fodder, fuel, and industrial purposes, including brewing/malting, starch extraction, the preparation of value-added products, and the manufacture of poultry and animal feed. Expanding the area under coarse cereals improves nutritional supply (protein and iron), increases climate resilience, reduces GHG emissions, and reduces demand for irrigation water and energy while maintaining calorie production and cropped area (Davis *et al.*, 2019). Thus, augmenting millet production helps achieve the SDGs: Goals 2 (attaining zero hunger), 3 (good health and well-being), 12 (sustainable consumption and production), and 13 (climate action) (Ceasar and Maharajan 2022, news.un.org).

In recent years, recognizing its enormous benefits, the Government of India has introduced various policies to increase millet production and consumption. These include 'The Initiative for Nutritional Security through Intensive Millets Promotion (INSIMP)' launched in 2011-12; the inclusion of coarse cereals under the National Food Security Act, 2013, in order to provide subsidized food grains through the public distribution system (PDS); and an increase in minimum support price of millets (DMD, 2014). The government of India termed millet "Nutri-cereals" to promote its production and consumption. Also, the government declared 2018 as the National Year of Millets to promote nutritional security. The United Nations General Assembly (UNGA) declared 2023 the International Year of Millets following India's endorsement, supported by other countries, to raise awareness of millets and their cultivation. In this context, the present study explores the production and consumption of millets in India and outlines a way forward to improve their production and consumption.

Status of millet cultivation in India

India is the largest producer of millets in the world, accounting for around 41% of global production in 2020, and the fifth-largest exporter, with exports valued at USD 26.97 million (pib.gov.in). In India,

a variety of millets are grown to suit different agro-climatic conditions. These include Sorghum (*Sorghum bicolor*), Pearl millet (*Pennisetum glaucum L.*), Finger millet (*Eleusine coracana L.*), and minor millets like Barnyard millet (*Echinochloa frumentacea L.*), Proso millet (*Panicum miliaceum L.*), Kodo millet (*Paspalum scrobiculatum L.*), Little millet (Kutki), and Foxtail millet (*Setaria italica L.*). Nutri-cereals hold a share of 11.15 percent of the gross cropped area under food grains in the country. It also constitutes 18.76 percent of the area and 15.89 percent of total food grain production in the country as of 2021-22 (GoI, 2022). They are primarily cultivated in resource-poor areas, and the area under irrigation is only 11.10 percent in the case of Bajra and 15.20 percent in the case of Jowar, which is far below in comparison to all food grains together (56.96 %) during 2019-20 (GoI, 2022). Traditionally, millet was widely produced and consumed in India and was grown in equal areas to rice and wheat. However, as a result of skewed policies favoring the production of rice and wheat post-green revolution, the area under nutri-cereals has been reduced by 37 percent between 1950-51 and 2020-21.

Figure 1 indicates the trend in area, production, and productivity of different millets. Triennium Ending (TE) averages between 1971 and 2021 indicate reductions of 40%, 75.70%, 59.24%, and 90.49% for Bajra, Jowar, Ragi, and Small Millets, respectively. At the same time, production has decreased for all millets except Bajra. Bajra production has increased by 74% owing to a ~3-fold increase in yield. The reduction in production was comparatively higher for minor millets (81%), followed by jowar (53%) and ragi (16%).

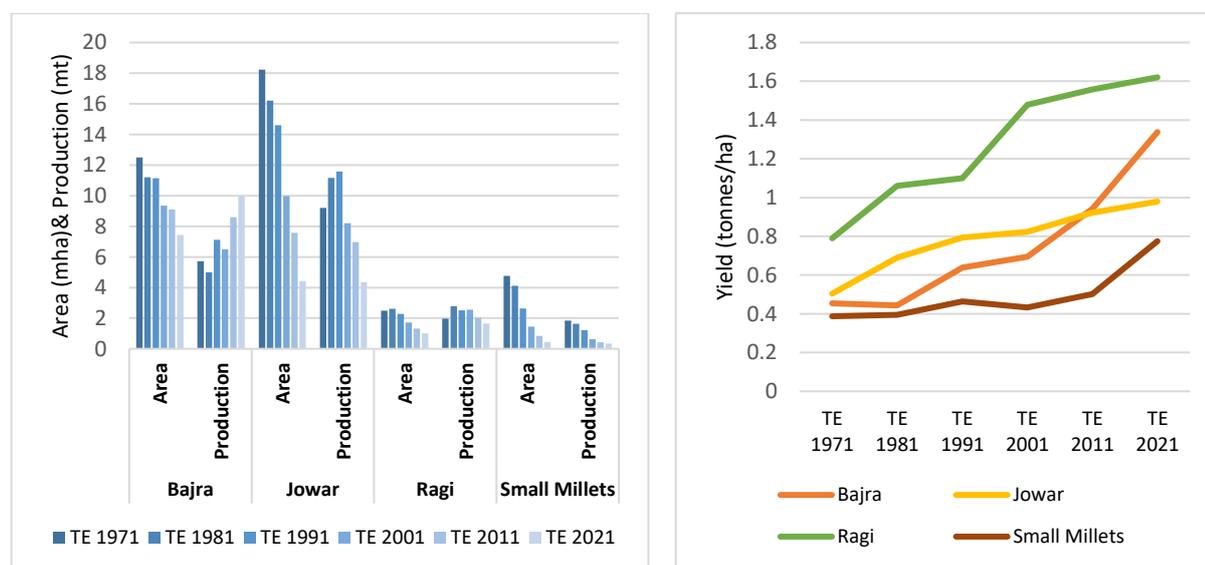


Fig 1: Change in area, production, and productivity of millets at all India levels from TE 1971 to TE 2021

Productivity has increased across all millets, with a comparatively higher increase in Bajra (~3 times), while it has almost doubled in the other millets. The area reduction has not been accompanied by a corresponding increase in yield in the case of all millets except Bajra. This may be attributed to the relatively large number of varieties released for Bajra, with a total of 167 hybrids and 61 varieties identified and released for cultivation through the ICAR-All India Co-ordinated Research Project (AICRP) on Pearl millet (Satyavathi *et al.*, 2018). The number of varieties/cultivars released for jowar, Ragi, and small millet is, respectively, 65, 54, and 34 (Sreekala *et al.*, 2022).

State-wise distribution

Millet cultivation is concentrated in a few districts across a few states. Table 1 shows the top three states for area, production, and yield of different millets based on the average TE 2021. In all cases, the top-producing states are not the most productive. Hence, there is scope to improve productivity in the top states by adopting improved varieties and following good agricultural practices.

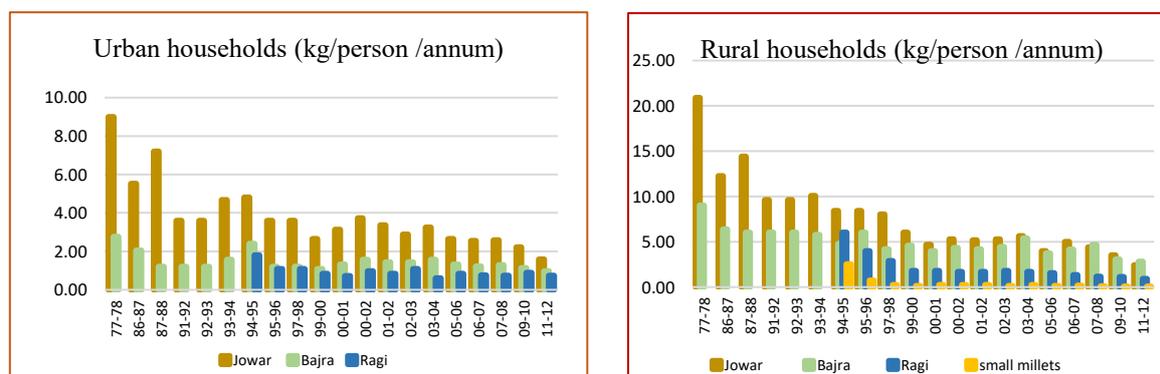
Table 1: Top states in terms of area, production, and yield for different millets

Millets	Top three states		
	Area (Share in %)	Production (Share in %)	Productivity (in tonnes/ha)
Bajra	Rajasthan (57.47) Uttar Pradesh (12.11) Maharashtra (8.83)	Rajasthan (43.68) Uttar Pradesh (19.18) Haryana (10.86)	Tamil Nadu (2.5) Gujarat (2.2) Haryana(2.2)
Jowar	Maharashtra (45.14) Karnataka(18.95) Rajasthan (13.29)	Maharashtra (33.90) Karnataka(21.30) Rajasthan(11.60)	Andhra Pradesh (2.47) Madhyapadesh (1.89) Telangana (1.44)
Ragi	Karnataka (63.94) Uttarakhand (8.67) Tamil Nadu(8.05)	Karnataka (64.33) Tamil Nadu (16.41) Uttarakhand (7.21)	Tamil Nadu (3.33) Karnataka (1.62) Uttarakhand (1.36)
Small millets	Madhyapadesh (18.51) Chattisgarh (17.27) Uttarakhand (11.65)	Uttarakhand (20.16) Madhyapadesh (19.26) Tamil Nadu (9.79)	Tamil Nadu(1.42) Uttarakhand (1.35) Arunachal Pradesh (1.03)

Note: Figures in parenthesis indicate the share in area and production in % and productivity in tonnes per hectare

Trend in Consumption

Millets were widely consumed in various recipes in India. However, various rounds of the National Sample Survey on Consumption expenditure data from 1977-78 to 2011-12 show a drastic reduction in consumption in rural and urban areas, as in Fig 2.

**Fig 2. Trend in consumption of millets; Source: Various rounds of NSSO data**

In rural households, the annual per-capita consumption has reduced from 20.88 to 3.6, 9 to 2.82, 6 to 0.06, and 2.52 to 0.06 Kg, respectively, for Jowar, Bajra, Ragi, and Small Millets. In urban households, the reductions were 9-1.58, 2.76-0.73, and 1.8-0.73 Kg, respectively, for Jowar, Bajra, and Ragi. The reduction in consumption is attributed to the availability of fine cereals such as rice

and wheat, which are relatively easy to prepare through PDS, whereas factors such as longer cooking times, difficulty in preparation, and the lack of value-added products contributed to the reduction in consumption of millets.

Way forward

Although millet is being promoted widely by state and central governments, some constraints limit its production and consumption. It was reported that there will be a deficit in jowar and minor millets in the near future if the past trend in production and consumption continues (Sreekala *et al.*, 2022). Although the scope for expanding the area is limited, incentivizing farmers to expand and bringing fallow lands under cultivation may help increase the area under cultivation. A primary survey conducted among farmers in Haryana and Madhya Pradesh revealed that the lack of quality seeds of improved varieties is a major constraint, and the majority of farmers use local varieties for cultivation. Also, farmers need to be made aware of the good agricultural practices that can improve productivity. As the major states in terms of area and production have relatively less productivity, focusing on productivity enhancement in these areas will help improve production.

Further, minimum support prices have been announced for Bajra, Jowar, and Ragi, not for minor millets. A study found that the price received by farmers cultivating minor millets ranges from Rs 1500 to Rs 3500 across various districts; hence, a stable price environment may encourage farmers to cultivate millets (Devi *et al.*, 2024). On the consumption front, the NSSO 68th round (2011-12) indicates that monthly per capita consumption is highest in the top-producing states, such as Rajasthan, Karnataka, Maharashtra, and Gujarat. Also, a study conducted by Potaka *et al.*, (2021) among urban consumers found that the main reason for non-consumption was not eating at home, followed by dislike of the taste. Hence, campaigns on social media and other mass media platforms about the nutritional and environmental benefits would help attract people to consume millet in non-traditional areas. Also, it is imperative to develop products that suit the palate of different consumer segments, which is critical to boosting consumption.

Furthermore, farmers need to be made aware of the prospects for processing millet. Forming farmers' groups, building capacity for processing technology, and marketing value-added products will help farmers realize higher incomes, which are otherwise less remunerative than those from competing crops. Finally, strengthening the millet value chain to serve national and international markets and encouraging private participation in processing are much needed to popularize millet.

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SMART AGRICULTURE FOR A WARMING WORLD: OPPORTUNITIES FOR INDIA'S FARMERS AND THE AGRI-INPUT INDUSTRY

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Abstract

Climate change is reshaping Indian agriculture through rising temperatures, erratic monsoons, soil degradation, and more frequent extreme events, with direct implications for fertiliser response, nutrient use efficiency (NUE), and farm profitability. While fertilisers have long underpinned national food security, conventional nutrient management is increasingly misaligned with climatic uncertainty. This paper examines key drivers of climate variability in India and their effects on crop productivity and fertiliser efficiency, and assesses fertiliser-centric mitigation and adaptation strategies. It highlights the role of enhanced-efficiency fertilisers, customised formulations, precision nutrient application, fertiliser - water integration, and digital advisory systems in improving resilience and lowering environmental losses. Selected industry initiatives, including IFFCO's Nano Urea Plus, Nano DAP, and biostimulants such as Sagarika, illustrate emerging responses to climate stress. The paper also discusses policy and institutional reforms- subsidy rationalisation, soil-test-based recommendations, and strengthened extension to scale climate-smart fertiliser adoption and support sustainable food and livelihood security in India.

Keywords: Climate-smart agriculture; fertiliser efficiency; nutrient use efficiency; monsoon variability; enhanced-efficiency fertilisers; India

Introduction

Indian agriculture is on the frontline of climate change, facing rising temperatures, increasing rainfall variability, and deteriorating soil health that threaten the productivity gains achieved during the Green Revolution. The country's diverse agro-ecological zones, ranging from the irrigated Indo-Gangetic plains to drought-prone southern peninsular regions, experience varying degrees of climatic stress, making farm-level nutrient management highly location-specific. Fertilisers have historically underpinned India's food security by enabling high crop yields, yet their effectiveness is increasingly constrained by climatic stress, soil degradation, and imbalanced nutrient use patterns. Excessive reliance on nitrogen, coupled with inadequate application of secondary and micronutrients, weakens crop resilience and reduces fertiliser response. Misalignment between nutrient timing and unpredictable weather events further exacerbates losses through leaching, volatilisation, and runoff, contributing to environmental pollution and greenhouse gas emissions (Bhattacharyya *et al.*, 2015; Pathak *et al.*, 2021).

In this context, climate-smart agriculture requires a paradigm shift in fertiliser management that goes beyond yield maximisation to emphasise resource-use efficiency, resilience to climatic shocks, and environmental sustainability. Technological innovations such as enhanced-efficiency fertilisers, nano-formulations, and precision application systems, combined with integrated nutrient management practices, offer pathways to improve nutrient use efficiency (NUE) under variable conditions. Managerial and policy interventions—ranging from soil-test-based recommendations

to subsidy rationalisation and digital advisory services—are critical enablers of adoption at scale. This paper examines the drivers of climate uncertainty in India, their impact on crop productivity and fertiliser efficiency, and explores fertiliser-centric mitigation and adaptation strategies as a lever for building climate-resilient Indian agriculture.

Drivers of Climate Uncertainty in India

Climate uncertainty in India emerges from a complex interplay of atmospheric, oceanic, land-use, and human-induced factors. The country's diverse agro-ecological zones amplify both spatial and temporal variability in temperature, rainfall, and extreme events, making nutrient management increasingly location-specific and challenging. Understanding these drivers is essential for designing fertiliser strategies that maintain crop productivity and nutrient use efficiency under changing climatic conditions.

Monsoon Variability and Rainfall Uncertainty: The southwest monsoon provides approximately 80% of India's annual rainfall and is the primary determinant of agricultural productivity. Recent decades have witnessed significant variability in monsoon onset, intra-seasonal dry spells, early withdrawal, and extreme rainfall events. Such irregularities disrupt sowing schedules and fertiliser application timing, leading to suboptimal nutrient uptake and losses. Heavy rainfall events accelerate nutrient losses through surface runoff, soil erosion, leaching, and denitrification, while prolonged dry spells reduce soil moisture and limit nutrient diffusion to crop roots (Sharma *et al.*, 2020). Consequently, conventional blanket fertiliser schedules often fail to match crop demand under these fluctuating conditions, emphasizing the need for adaptive, weather-responsive nutrient strategies.

Rising Temperatures and Heat Extremes: India has experienced a warming trend of approximately 0.7°C over the last century, with projections suggesting a rise of 1.5–2.0°C by mid-century. Elevated temperatures shorten crop growth periods, impair root development, and accelerate soil nitrogen losses through volatilisation. These physiological and biochemical effects reduce nutrient uptake efficiency and yield potential, particularly for nitrogen-intensive crops (Singh *et al.*, 2018). Heat stress also exacerbates water demand, further constraining fertiliser effectiveness under water-limited conditions.

Ocean–Atmosphere Interactions: Large-scale climate phenomena such as the El Niño–Southern Oscillation (ENSO), Indian Ocean Dipole (IOD), and Madden–Julian Oscillation (MJO) strongly influence monsoon variability. The increasing unpredictability of these phenomena complicates fertiliser planning and risk management at the farm level, as crop nutrient demand may no longer coincide with traditional fertiliser application schedules (Roxy *et al.*, 2017; Goswami *et al.*, 2021).

Land-Use Change and Soil Degradation: Rapid urbanisation, deforestation, residue removal, and continuous intensive cultivation have diminished soil organic carbon and nutrient buffering capacity. Degraded soils exhibit lower fertiliser response and greater vulnerability to climatic stress, reducing both productivity and NUE. Soil erosion and nutrient depletion create long-term constraints on sustainable nutrient management, requiring integration of organic amendments and conservation practices.

Industrialisation and Aerosols: Industrial emissions and aerosol concentrations alter the Earth's radiation balance, cloud formation, and local rainfall patterns. These indirect effects exacerbate heat stress and alter nutrient availability in soils, complicating fertiliser efficiency and crop response (Kumar *et al.*, 2020).

Glacial Retreat and Water Resources: Accelerated melting of Himalayan glaciers threatens base flows of major river systems, reducing the reliability of irrigation in downstream regions. Limited

water availability constrains nutrient uptake, diminishes fertiliser efficiency, and increases the risk of crop failure during dry periods (Gupta *et al.*, 2021).

Population Pressure and Intensification: Rising food demand has led to intensified fertiliser use, predominantly nitrogen-based. This imbalance contributes to soil nutrient depletion, environmental pollution, and higher greenhouse gas emissions, reinforcing climate–agriculture feedback loops (Pathak *et al.*, 2021).

Regional Topography and Agro-Ecological Diversity: India's diverse topography—from the heat-stressed Indo-Gangetic plains to drought-prone southern peninsular zones—creates significant spatial heterogeneity in climate risks and fertiliser responsiveness. Location-specific nutrient management strategies are therefore critical for effective climate adaptation.

Socioeconomic Drivers: Limited access to credit, weak extension services, and distortions in fertiliser policy, especially subsidy imbalances, amplify vulnerability to climate stress. These socioeconomic constraints hinder adoption of adaptive nutrient practices and reduce farmers' resilience to climatic shocks (Kumar *et al.*, 2020).

Feedback Mechanisms: Loss of soil carbon, vegetation cover, and moisture retention exacerbates regional climate variability by altering local microclimates. These feedback mechanisms reduce fertiliser responsiveness, reinforce nutrient inefficiencies, and perpetuate cycles of environmental and agronomic vulnerability (Roxy *et al.*, 2017).

Collectively, these drivers underscore the necessity for adaptive, location-specific, and integrated nutrient management strategies in India. Fertiliser interventions must account for complex climatic, ecological, and socioeconomic interactions to enhance resilience, optimise resource use, and sustain agricultural productivity in the face of mounting climate uncertainty.

Impact of Climate Uncertainty on Indian Agriculture

Climate variability exerts profound effects on crop physiology, soil processes, and fertiliser response in India, where agriculture remains highly sensitive to weather fluctuations. Rising temperatures restrict nutrient uptake by impairing root development, accelerating plant metabolism, and increasing nitrogen volatilisation losses. As a result, crops under heat stress often fail to utilize applied nitrogen efficiently, reducing yield potential and increasing environmental nitrogen losses (Singh *et al.*, 2018). Similarly, erratic rainfall patterns—ranging from high-intensity floods to prolonged dry spells—further compromise nutrient availability. Heavy precipitation events cause substantial nutrient wash-off through runoff and leaching, while drought conditions limit nutrient diffusion and root absorption, diminishing fertiliser efficacy (Sharma *et al.*, 2020).

Declining groundwater levels and reduced irrigation reliability exacerbate these challenges, particularly in water-stressed regions such as northwest India and parts of the peninsular south. Inadequate water availability constrains nutrient uptake and limits the effectiveness of conventional fertiliser application, highlighting the critical need for integrated water–nutrient management strategies to maintain crop productivity under changing climatic conditions (Gupta *et al.*, 2021).

Climate stress also affects pest and disease dynamics, increasing the vulnerability of crops to biotic pressures. Imbalanced nutrient management—particularly over-reliance on nitrogen with insufficient phosphorus, potassium, sulphur, and micronutrients—further compromises plant health, reducing resistance to pathogens and abiotic stress (Kumar *et al.*, 2020). Decades of nitrogen-centric fertilisation have degraded soil organic carbon, lowered nutrient buffering capacity, and weakened overall fertiliser response, thereby destabilising yields.

Under such conditions, even higher fertiliser doses often fail to produce proportional yield gains, raising production costs and increasing environmental losses through leaching, volatilisation, and greenhouse gas emissions (Pathak *et al.*, 2021). These agronomic challenges translate into economic consequences, including income instability, increased rural vulnerability, and heightened risks to national food security.

At a system level, climate uncertainty disrupts agricultural GDP, affects agri-input demand, and influences allied sectors such as food processing, storage, and marketing. Simultaneously, these challenges create opportunities for innovation in fertiliser technologies, adaptive nutrient management practices, and digital advisory services that integrate weather forecasting, soil health monitoring, and precision application techniques to mitigate climate impacts (Ramakrishna *et al.*, 2021).

By understanding the multi-dimensional effects of climate variability on crops, soils, and fertiliser response, policymakers, researchers, and industry stakeholders can develop targeted strategies that enhance resilience, improve resource-use efficiency, and safeguard both productivity and livelihoods under a warming climate (**Fig.1**).



Fig. 1 Impact of Climate uncertainty on agriculture

Fertiliser-Centric Mitigation and Adaptation Strategies

Fertiliser-centric mitigation and adaptation strategies form the cornerstone of climate-smart nutrient management in agriculture. As climate change intensifies temperature stress, rainfall variability, and resource constraints, fertiliser practices must evolve beyond yield maximisation toward resilience building and environmental stewardship. Mitigation-oriented strategies focus on reducing agriculture's climate footprint by enhancing nutrient use efficiency, minimising nitrogen losses, and lowering greenhouse gas emissions, particularly nitrous oxide. In contrast, adaptation strategies emphasise stabilising crop yields and strengthening soil and plant resilience under climatic extremes through balanced nutrition, improved soil health, and synchronised nutrient–water management. Together, these complementary approaches position fertilisers not merely as yield-enhancing inputs but as strategic tools for sustaining productivity, profitability, and ecological integrity in a warming and increasingly uncertain agricultural landscape.

Fertiliser-Centric Mitigation Strategies

Fertiliser-centric mitigation strategies focus on reducing agriculture's contribution to climate change by lowering greenhouse gas (GHG) emissions and minimising nutrient losses to air and water, while maintaining crop productivity. Among agricultural emissions, nitrous oxide (N₂O) from inefficient nitrogen use is particularly significant. Improving nutrient use efficiency (NUE) therefore lies at the core of mitigation-oriented fertiliser management. Site-specific nutrient management (SSNM) and balanced fertilisation reduce excessive nitrogen application by aligning nutrient doses with crop demand, soil nutrient status, and prevailing climatic conditions. By avoiding over-fertilisation, SSNM directly curtails N₂O emissions, ammonia volatilisation, and nitrate leaching (Pathak *et al.*, 2021).

Enhanced-efficiency fertilisers (EEFs) represent a major technological lever for mitigation. Controlled-release fertilisers, coated urea, nitrification and urease inhibitors, slow-release formulations, and nano-fertilisers improve synchrony between nutrient release and crop uptake. This synchronisation reduces nitrogen losses through volatilisation, leaching, and denitrification—processes that intensify under high temperatures and erratic rainfall. Empirical evidence shows that EEFs can significantly lower N₂O emissions per unit of yield while maintaining or improving productivity (Singh *et al.*, 2020). Indian innovations such as Nano Urea Plus and Nano DAP demonstrate how formulation science can reduce total fertiliser consumption and the carbon footprint associated with fertiliser manufacture, transport, and application (IFFCO, 2022).

Precision nutrient application technologies further strengthen mitigation outcomes. GPS-enabled machinery, variable-rate applicators, and automated spreaders allow fertilisers to be applied only where and when they are required. This spatial and temporal precision minimises nutrient runoff during intense rainfall events and reduces gaseous losses under heat stress, thereby lowering indirect emissions from fertiliser mismanagement (Ramakrishna *et al.*, 2021). Similarly, fertigation and micro-irrigation systems enhance fertiliser–water synergy, reducing both energy use and nutrient losses.

Integrated nutrient management (INM), which combines chemical fertilisers with organic amendments, crop residues, and biofertilisers, contributes to mitigation by improving soil organic carbon stocks and nutrient retention. Higher soil carbon not only enhances nutrient efficiency but also sequesters atmospheric carbon dioxide, creating co-benefits for climate mitigation. Collectively, fertiliser-centric mitigation strategies reduce emission intensity—emissions per unit of output—supporting national climate commitments while sustaining agricultural productivity.

Fertiliser-Centric Adaptation Strategies

Fertiliser-centric adaptation strategies aim to enhance the capacity of crops, soils, and farming systems to cope with climate variability and extremes such as droughts, heat stress, and erratic rainfall. In a changing climate, yield stability becomes as important as yield maximisation. Nutrient management plays a critical adaptive role by strengthening plant physiological resilience and improving soil properties that buffer climatic shocks (**Fig. 1**).

Site-specific nutrient management (SSNM) is central to adaptation because it tailors fertiliser application to local soil conditions, crop growth stages, and weather patterns. By ensuring timely and adequate nutrient supply, SSNM helps crops withstand stress conditions such as delayed monsoons or heat waves. Balanced fertilisation—including secondary and micronutrients—enhances root development, photosynthetic efficiency, and stress tolerance, reducing the vulnerability of crops to climatic fluctuations (Pathak *et al.*, 2021).

Enhanced-efficiency fertilisers (EEFs) also contribute strongly to adaptation. Controlled-release and slow-release formulations ensure sustained nutrient availability even when rainfall is irregular or irrigation is constrained. Under drought or heat stress, conventional fertilisers often fail to synchronise with crop demand, leading to nutrient deficiency at critical stages. EEFs mitigate this risk by maintaining nutrient supply over longer periods, thereby stabilising yields under adverse conditions (Singh *et al.*, 2020). Nano-fertilisers further support adaptation by improving nutrient uptake efficiency at lower application rates, reducing dependency on repeated fertiliser applications during uncertain weather.

Integrated nutrient management enhances adaptive capacity at the soil level. Incorporating organic amendments, crop residues, biofertilisers, and bio-stimulants improves soil organic carbon, water-holding capacity, and aggregate stability. These improvements enable soils to retain moisture during dry spells and drain excess water during heavy rainfall, buffering crops against climate extremes. Healthier soils also support beneficial microbial activity, which enhances nutrient cycling and long-term soil fertility.

Fertiliser–water synergy is another critical adaptation pathway. Micro-irrigation, drip systems, and fertigation allow precise nutrient delivery in synchrony with limited water availability, making them particularly valuable in drought-prone regions. When combined with digital advisory platforms that integrate weather forecasts, soil moisture data, and nutrient status, farmers can make adaptive, real-time decisions on fertiliser timing and dosage (Ramakrishna *et al.*, 2021).

Overall, fertiliser-centric adaptation strategies strengthen resilience by stabilising yields, improving soil health, and reducing production risks under climate uncertainty. By embedding these approaches within climate-smart agriculture, fertiliser management becomes a proactive tool for coping with both current and future climatic stresses.

Policy Implications

Policy alignment is critical for scaling climate-smart fertiliser practices across India's diverse agro-ecological regions. Rationalising fertiliser subsidies to discourage excessive nitrogen use and incentivise balanced application of phosphorus, potassium, sulphur, and micronutrients is essential for improving nutrient use efficiency and soil health. Shifting subsidy support towards enhanced-efficiency fertilisers, customised formulations, and nano-fertilisers can encourage farmers to adopt technologies that reduce nutrient losses under climatic stress.

Integrating Soil Health Card data with digital decision-support platforms and weather-based advisories will enable location-specific, climate-responsive nutrient recommendations. Strengthening extension systems through capacity building, use of ICT tools, and collaboration with private input providers and cooperatives can improve last-mile delivery of climate-smart practices (Pathak *et al.*, 2021). Public–private partnerships, particularly with fertiliser manufacturers and agri-tech firms, can facilitate farmer training, field demonstrations, and feedback-driven innovation. Collectively, these policy measures can align fertiliser use with climate resilience goals while maintaining productivity and environmental sustainability.

Way Forward

Enhanced-efficiency and customised fertilisers, including controlled-release, nano, and bio-based formulations, can align nutrient supply with crop demand, reduce losses, and improve resilience under climatic stress. Precision nutrient management, leveraging soil testing, remote sensing, and decision support tools, can optimise timing, placement, and dosage, while integrating water–nutrient strategies ensure efficient resource use.

Policy and institutional reforms are equally critical. Fertiliser subsidies must incentivise balanced nutrition rather than volume, Soil Health Card data should be integrated with real-time digital advisories, and public–private partnerships strengthened to scale adoption. Simultaneously, farmer capacity building and technology-enabled advisory services can bridge the gap between innovation and practice.

Integrating fertiliser strategies within broader climate-smart agriculture frameworks—linking nutrient management with conservation agriculture, adaptive cropping systems, and integrated pest management will further enhance resilience, reduce emissions, and promote sustainable intensification.

Epilogue

The shifting climate has irrevocably transformed the risk landscape of Indian agriculture, revealing the limitations of conventional fertiliser practices. Rising temperatures, erratic rainfall, and ongoing soil degradation have exposed the shortcomings of nitrogen-centric, blanket recommendations, highlighting the urgent need to enhance nutrient use efficiency. In this evolving context, fertilisers must be seen not just as yield-enhancing inputs, but as strategic instruments for both climate adaptation and mitigation. This paper underscores that fertiliser-centric, climate-smart pathways grounded in enhanced-efficiency fertilisers, customised nutrient formulations, precision application, fertiliser–water integration, and digital advisory systems can significantly strengthen yield stability, resource-use efficiency, and environmental performance under variable climatic conditions. Innovations such as nano-fertilisers and bio-stimulants exemplify how technological advances can align nutrient delivery with crop demand and climatic stress. Yet, technology alone cannot drive transformation. Effective policy and institutional support are equally critical. Rationalising fertiliser subsidies to promote balanced nutrition, integrating Soil Health Card data with real-time advisory platforms, enhancing extension services, and fostering public–private collaborations are essential for scaling adoption. Fertiliser policy must evolve from a volume-driven approach to one focused on efficiency, resilience, and sustainability. By embedding fertiliser management within a comprehensive climate-smart agriculture framework, India can safeguard past productivity gains, mitigate environmental impacts, and strengthen the resilience of its farming systems. In doing so, the nation can secure food security and protect farmer livelihoods amidst the uncertainties of a warming world.

Conclusion

A fertiliser-centric, climate-smart pathway offers India a dual advantage: protecting past productivity gains while transforming agriculture into a resilient, low-emission, and resource-efficient system. By combining technological innovations, precision management, and supportive policies, Indian agriculture can stabilize yields under climatic variability, optimize resource use, and safeguard environmental quality. Ultimately, embedding fertiliser management within a comprehensive climate-smart framework will secure farmer livelihoods, ensure food and nutritional security, and position India to thrive in an increasingly uncertain and warming world.

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TRADITION, COMMUNITY, AND CHANGING SEASCAPES: SMALL-SCALE FISHING AMONG THE RAMPONKARS OF GOA

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Abstract

The Ramponkars of Goa represent the heart of small-scale fishing along India's coastline. Their traditional rampon fishing method relies on shared labour, simple gear, and deep knowledge of local seas, making it both sustainable and community-driven. Today, like many small-scale fishers, they face growing challenges from declining fish stocks, mechanized fishing, and rising living costs. Yet, they continue to survive and adapt by protecting their traditional practices, using technology carefully, and finding seasonal and supplementary livelihoods such as tourism. Through collective organisations like GRE and the National Fisher workers Forum, the Ramponkars highlight the importance of small-scale fisheries in ensuring food security, coastal livelihoods, and the long-term health of marine ecosystems.

Keywords: Small-scale fisheries, Ramponkar, Traditional fishing practices, Coastal communities, Sustainable marine livelihoods.

Introduction

Small-scale fisheries form the backbone of coastal communities worldwide, sustaining food security, livelihoods, cultural identity, and social cohesion (Béné *et al.*, 2007; Townsley, 2013; Belton & Thilsted, 2014; Vianna *et al.*, 2020). In India, small-scale fisheries dominate the marine sector, contributing nearly 70–80% of total marine fish landings through artisanal methods and small fishing vessels (Jena & George, 2018). Operating with low-impact gears such as gillnets, hook-and-line systems, and beach seines, and relying largely on non-mechanized or low-powered boats, these fishers harvest selectively while minimizing ecological disturbance. Beyond economic activity, small-scale fishing represents a way of life, long shaped by the cultural, social, and ecological landscapes of India's coastline. In recent decades, however, the seascape within which the small-scale fisheries operate has undergone significant transformation. The expansion of mechanized and motorized fishing fleets has intensified competition for marine resources, often marginalizing traditional artisanal fishers who rely on low-impact gear and nearshore waters. At the same time, coastal development, tourism, port expansion, and industrial pollution have reduced access to fishing grounds and degraded marine ecosystems. Policy shifts emphasizing export-oriented fisheries, aquaculture, and centralized governance have further reshaped livelihood patterns, weakening customary management systems and community-based institutions. Together, these changes have altered labor relations, knowledge transmission, and social organization within fishing communities, compelling small-scale fishers across India to adapt through diversification of livelihoods, collective mobilization, and renewed claims over rights, sustainability, and social justice.

Goa is a small coastal Union Territory with many bays and rocky headlands, and small scale fishing plays an important role in the state. In Goa, fish is more than just food, it is a part of everyday life and culture (DoF-GoG, 2022). Most people eat fish curry and rice almost every day, and even missing fish for a short time is strongly felt. This shows how closely Goans are connected to the sea and depend on it for their daily lives. Along the coastline of Goa, there are many traditional fishing villages. These villages are home to fishing communities like the Kharvis and their sub-groups such as the Ramponkars, Magkars, Kantaikars, Pagelkars, and Arrikars (D’Cruz & Raikar, 2004). In earlier times, each group fished in specific coastal areas and used different types of nets and fishing tools designed to catch kinds of fish. These fishing practices were based on long experience and deep knowledge of the sea, which was passed down from one generation to the next. Among these communities, the Ramponkars represent a distinctive maritime community whose livelihood is deeply embedded in collective labour, customary norms, and an intimate knowledge of the sea. This article investigates how the Ramponkars of Goa represent a distinctive maritime community that navigate these changing seascapes, examining the tensions between tradition and transformation while highlighting the resilience and adaptive strategies of small-scale fishing communities in the face of socio-economic and environmental change.

The case study of Ramponkars

The Ramponkars are among the oldest fishing communities in Goa, known for their traditional method of rampon fishing, where large nets are pulled from the shore by many hands working together. The word *rampon* itself comes from Goa’s colonial past, derived from the Portuguese word *rapão*, meaning a large drag-net, and over time it became part of the local Konkani language. Villages like Velsao in South Goa grew around this tradition, where daily life followed the rhythm of the tides and the seasons. Rampon fishing depends heavily on teamwork and experience.



Figure 1. Collective hauling of the rampon net by fishers from both ends of the rope along the shoreline.

Different types of nets (*Bodiye Rampon* and *Dandiya Rampon*) are used based on the season and the sea conditions, and successful fishing requires careful reading of tides, currents, and fish movement. The actual hauling of the net is physically demanding and can take several hours, with dozens of people pulling together from the shore. Often, songs and chants help keep everyone in

rhythm, turning hard labour into a shared emotional and social experience. The post-monsoon period, from September to December, marks the peak fishing season. The catch usually contains sardines, mackerel, crabs, and shrimp. Traditionally, rampon fishing was a collective community activity that involved everyone, men, women, and children in handling and sharing the catch. Women played a key role in cleaning, drying, and preserving fish, while leftovers were reused as manure or bird feed, showing a strong no-waste practice. Catch-sharing systems evolved over time, moving from unequal divisions to fairer arrangements between net owners and workers. When fish catches were large, fishermen used simple but effective methods to keep fish fresh—submerging excess fish in shallow waters along the shore, reflecting the Ramponkars' traditional knowledge base.

The sense of togetherness among the Ramponkars has always gone beyond individual villages. Fishermen once travelled from far-off coastal areas to places like Velsao to learn rampon fishing, sharing skills and experiences. This spirit of unity later took shape through organisations such as the Goenchea Ramponkarancho Ekvott (GRE), formed in 1975 to represent traditional fishing communities across Goa. Over time, however, changes in fishing rules, technology, and coastal development have made life harder for small-scale fishers. While older fishermen remember plentiful catches, today's Ramponkars speak of fewer fish, higher costs, and growing pressure from mechanized boats. In response, they have come together to protest, demand fair regulations, and protect their fishing spaces. For the Ramponkars, this struggle is not just about earning a living, it is about defending small-scale fishing, their way of life, and their deep connection to the sea.

Faced with declining fish stocks, rising costs, and increasing competition from mechanized fishing, the Ramponkars have adopted a range of adaptation strategies to sustain their livelihoods. Many have diversified their sources of income by migrating for work, taking up jobs in construction, hospitality, or combining fishing with tourism-related activities such as dolphin-watching and coastal trips. Those who continue fishing have selectively adopted motorised boats to reach farther waters while consciously avoiding destructive practices like trawling and purse seining, reflecting a strong commitment to sustainability. Seasonal fishing, especially during the post-monsoon period and the mechanized fishing ban, remains crucial, with short but productive fishing windows supporting household incomes. Alongside these livelihood adjustments, Ramponkars actively engage in collective advocacy through organisations like GRE, demanding stronger regulations and longer fishing bans to protect marine resources. Together, these strategies show how small-scale fishers adapt not by abandoning tradition, but by balancing survival, sustainability, and cultural identity in a rapidly changing seascape.

Reflective feedback for protecting the small-scale fisheries in India.

Protecting small-scale fisheries in India can draw important lessons from the experience of the Ramponkars of Goa. First, their use of low-impact, cooperative fishing methods shows the need to prioritise and protect traditional gear that is environmentally sustainable. Second, the Ramponkars' collective labour and community-based sharing systems highlight the importance of strengthening local institutions and fisher cooperatives. Third, their struggles against mechanised fishing underline the need for strict enforcement of coastal fishing regulations to safeguard nearshore waters for small-scale fishers. Fourth, their adaptive strategies such as seasonal fishing and livelihood diversification suggest that policy support should focus on flexibility rather than forced modernisation. Finally, the role of organisations like GRE demonstrates that fisher-led advocacy and participation are crucial for effective fisheries governance. Together, these reflections show that

protecting small-scale fisheries is not only about conserving fish stocks, but also about sustaining communities, cultures, and traditional ways of life.

Conclusion

Small-scale fisheries remain central to coastal livelihoods, food security, and cultural identity in India and worldwide. The experience of the Ramponkars of Goa shows that small-scale fishing is not just an economic activity but a way of life rooted in collective labour, traditional knowledge, and close ties to coastal ecosystems. Despite growing pressures from mechanization, coastal development, and environmental change, these communities have shown strong resilience through seasonal fishing, selective use of technology, livelihood diversification, and collective action. Their story highlights the need for strong community institutions, fair enforcement of regulations, and meaningful participation of fishers in decision-making. Protecting small-scale fisheries therefore requires policies that recognise their social, cultural, and ecological value, ensuring sustainable marine resources alongside equitable and inclusive coastal development.

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IMPROVING THE NUTRITIONAL PROFILE OF LIVE FEEDS IN AQUACULTURE

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Introduction

Aquaculture has emerged as one of the fastest growing food producing sectors worldwide and playing a crucial role in meeting the increasing demand for aquatic protein. Among the many factors influencing the success of aquaculture operations, nutrition during early life stages is one of the most critical. Fish and shellfish larvae possess delicate digestive systems and limited feeding capabilities, making them highly dependent on live feeds during their initial developmental phases. Live feeds such as phytoplankton and zooplankton are often referred to as “living nutritional capsules” because they contain essential macro- and micronutrients required for larval growth. Their natural movement in the water column stimulates feeding responses in larvae, making them far more acceptable than inert or formulated feeds. However, despite their advantages, many commonly used live feeds are nutritionally deficient, particularly in essential fatty acids, amino acids, vitamins, and minerals. This limitation necessitates the nutritional enrichment of live feeds to improve larval survival, growth, and overall quality.

Importance of Live Feeds in Larviculture

Live feeds play an indispensable role in both freshwater and marine hatchery systems. Newly hatched larvae often lack a fully developed digestive tract and enzyme system, which restricts their ability to digest artificial feeds. Live feeds, being soft-bodied and easily digestible, provide nutrients in a form that larvae can readily assimilate. In addition to digestibility, live feeds help maintain water quality by remaining alive until consumed, thereby reducing feed wastage and organic pollution. They also contain bioactive compounds such as enzymes, hormones, pigments, and immune-enhancing substances that are often absent in formulated diets. Consequently, live feeds are considered essential for successful larval rearing, especially during the first feeding stages.

Nutritional Enhancement of Major Live Feed Groups

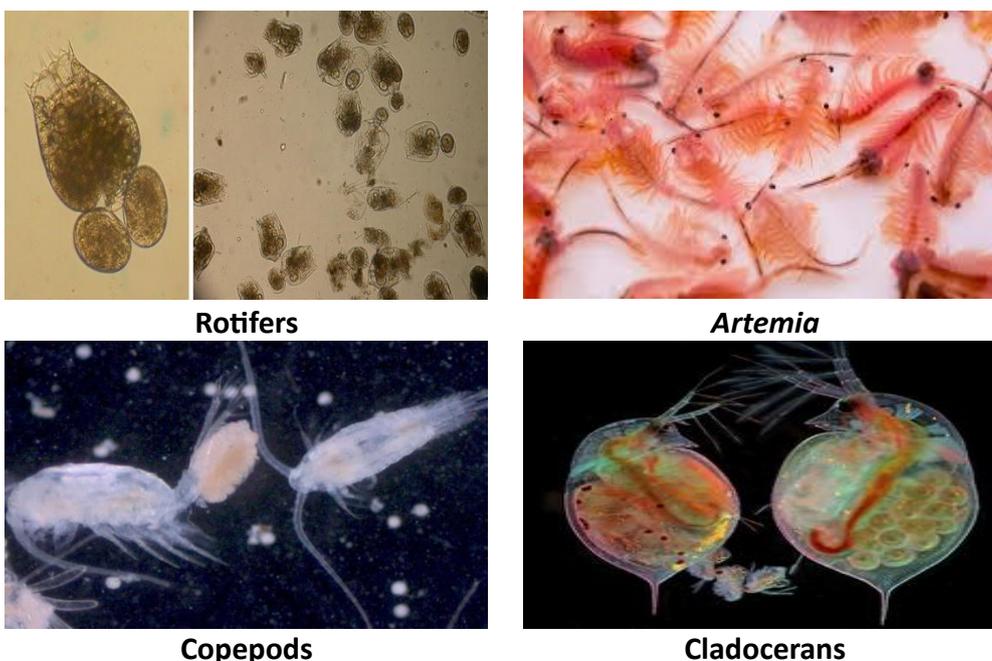
Rotifers

Rotifers are among the most commonly used starter feeds in aquaculture due to their small size, high reproductive rate, and ease of mass culture. However, their nutritional value depends entirely on what they consume. Rotifer enrichment is typically achieved using microalgae, yeast, oil emulsions, or commercial enrichment products. Microalgae such as *Nannochloropsis* and *Isochrysis* are particularly valuable as they are rich in essential fatty acids. Oil-based emulsions and commercial diets are also widely used to boost DHA and EPA levels. Additionally, rotifers can be enriched with specific vitamins and minerals to address larval deficiencies and improve skeletal development.

Artemia

Artemia nauplii are extensively used in hatcheries because of their convenient cyst storage, easy hatching, and suitability for a wide range of species. Nevertheless, newly hatched *Artemia* are

naturally low in essential fatty acids and must be enriched before use. *Artemia* enrichment involves exposing nauplii to lipid emulsions, microalgae, or encapsulated nutrient particles. This process significantly enhances their fatty acid profile, making them more suitable for marine fish larvae. Enriched *Artemia* have been shown to improve larval growth, survival, stress tolerance, and resistance to deformities.

**Rotifers****Artemia****Copepods****Cladocerans****Fig. Major live feed groups**

Copepods

Copepods are considered nutritionally superior to both rotifers and *Artemia* because of their high levels of DHA, EPA, amino acids, vitamins, and digestive enzymes. They closely resemble the natural prey of marine fish larvae, making them highly suitable for larviculture. Unlike other live feeds, copepods are difficult to enrich through short-term exposure. Instead, their nutritional profile is improved by manipulating their culture diet, particularly through the use of nutrient-rich microalgae. Although copepods offer excellent nutritional benefits, challenges related to large-scale production and cost currently limit their widespread use.

Cladocerans

Cladocerans such as *Moina* and *Daphnia* are important live feeds in freshwater aquaculture. They are easy to culture, reproduce rapidly, and contain high protein levels. However, their fatty acid composition is often inadequate for optimal larval development. Nutritional enhancement of cladocerans can be achieved by feeding those enriched microalgae, oil emulsions, or agricultural by-products such as rice bran. Proper enrichment significantly improves their value as a substitute for *Artemia* in freshwater systems.

Nutritional Limitations of Conventional Live Feeds

Despite their widespread use, traditional live feeds such as Rotifers and *Artemia* often lack sufficient levels of highly unsaturated fatty acids (HUFAs) like docosahexaenoic acid (DHA), eicosapentaenoic acid (EPA), and arachidonic acid (ARA). These fatty acids are crucial for membrane formation, neural development, stress resistance, and immune function in fish larvae. Similarly, deficiencies in certain

amino acids, vitamins, and minerals can result in poor growth performance, skeletal deformities, delayed metamorphosis, and increased mortality. Since the nutritional profile of live feeds largely reflects their diet and culture conditions, nutritional manipulation or enrichment has become an essential practice in modern hatcheries.

Concept of Live Feed Enrichment

Live feed enrichment refers to the process of improving the nutritional quality of live organisms before they are fed to larvae. This is commonly achieved through bio-encapsulation, where live feeds ingest nutrient-rich particles that are later transferred to the target larvae.

Enrichment strategies can be broadly categorized into:

- Direct enrichment, where live feeds are exposed to nutrient-rich emulsions or microdiets for a short duration.
- Dietary manipulation, where live feeds are cultured on nutritionally superior diets such as microalgae or fortified feeds over a longer period.

Role of Vitamins and Minerals in Live Feed Enrichment

Vitamins and minerals are essential for metabolic processes, immune function, and skeletal development in fish larvae. Enriching live feeds with micronutrients such as vitamin C, vitamin E, iodine, selenium, zinc, and calcium has shown positive effects on larval growth and health. Although mineral enrichment is less commonly practiced than lipid enrichment, it represents an important area for future research, especially for reducing deformities and improving larval robustness.

Future Prospects and Challenges

The increasing demand for high-quality seed in aquaculture highlights the need for cost-effective, sustainable, and nutritionally optimized live feeds. While enrichment technologies have advanced significantly, challenges remain in maintaining consistent live feed quality, reducing costs, and scaling up production under hygienic conditions. Future research should focus on developing low-cost enrichment materials, exploring locally available live feed species, and improving culture systems. Innovations in bio-encapsulation and microdiet technology may further enhance the efficiency of live feed utilization.

Conclusion

Live feeds remain an irreplaceable component of larval nutrition in aquaculture. Although their natural nutritional composition is often insufficient, enrichment techniques have proven effective in enhancing their dietary value. By improving the quality of live feeds through targeted enrichment strategies, hatcheries can achieve higher larval survival, better growth performance, and improved stock quality. Continued advancements in live feed nutrition will play a key role in the sustainable expansion of aquaculture worldwide.

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ODOP - CIRCULAR BIO-ECONOMY CLUSTER: A NEW RURAL PARADIGM FOR INDIA

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Why Rural India Needs a Circular Bioeconomy?

India's agriculture system is always at the edge of transition point where productivity has increased in many crops, rural communities still face low farm incomes, high input cost, uncertain markets, improper post-harvest management, agri-waste disposal problems and limited local value addition enterprises. Simultaneously, rural areas possess enormous untapped bio-resources like crop residues, food-processing waste, livestock waste and agro-industrial by-products, that can be converted into high-value products.

This is where the idea of the ODOP - Circular Bio-economy Cluster (CBC) emerges shifting the conventional linear economic models. A model where each district's One District One Product (ODOP) becomes the anchor for decentralized processing systems, biowaste valorization, micro/small enterprise development, circular and regenerative value chains.

Literature over the last decade suggests that circular agriculture - recycling biomass, nutrients and energy - can raise farm incomes by 20 - 40%, reduce emissions by 30 - 50% and create new rural enterprises (Pal et al., 2024; Bahman et al., 2025; Discover Sustainability, 2024).

What is an ODOP - Circular Bio-economy Cluster?

An ODOP - CBC is an integrated district-level entrepreneurship ecosystem built around a single high-potential ODOP crop (mango, turmeric, millets, dairy, chili, banana etc.)/commodity (products developed from local handlooms, leather, fibre/coir, wooden art crafts etc.). It aims to convert nearly 100% of ODOP-linked biomass into usable products leveraging biological, thermo-chemical and mechanical processes.

The Cluster Includes 5 Value Streams

1. **Farmer Aggregation & Primary Production:** Farmer Producer Organizations (FPOs) consolidate inputs and raw material for production.
2. **Post-harvest Processing & Value Addition:** Food, fibre, coir, herbal or dairy processing units.
3. **By-product Valorization:** Turning husk, shells, straw, peels, slurry, pulp and rejects into biochar, biofertilizers, biogas, bio-compost, bioplastics and feed.
4. **Eco-Industrial Linkages:** MSMEs use the by-products as inputs for packaging, nutraceuticals, infrastructure, construction and insulation panels etc.
5. **Regenerative Farming Loop:** Returning biochar and compost to soil – creating circular nutrient cycle.

This aligns with research that agricultural biomass can be converted into 20+ marketable products through circular pathways (Kumar & Nagar, 2024; Santosh et al., 2021).

Why ODOP and Circular Bio-economy Fit Naturally Together?**ODOP provides specialization**

The ODOP initiative establishes specialization focusing on a single, well-known crop or commodity per district guarantees a consistent and reliable biomass supply. This concentration of feedstock allows for the development of localized biorefineries and waste-to-wealth units, achieving better economies of scale. Furthermore, the existing market demand and cultural familiarity simplify logistics and ensure greater stakeholder acceptance for converting crop residues into valuable bio-based products like biofuels and bio fertilizers/pesticides.

Circular bioeconomy adds value to waste

The Circular bioeconomy acts as a powerful lever for value creation by converting agro-industrial waste into revenue. Studies indicate that agro-industries typically generate substantial waste, ranging upto 60 % of their total output, depending on the specific commodity. By implementing circular conversion technologies, these residues which were costly liabilities once are presently transformed into high-value products.

FPOs and SHGs become enterprise drivers

Stakeholder Group	Primary Role in the Circular Bioeconomy	Contribution to Integration
FPOs	Aggregate raw material (biomass/crop residue).	Ensures reliable, consolidated feedstock supply for processing units.
SHGs	Operate micro-units (e.g., bio-fertilizers/pesticides, dried products, specialized packaging, composting).	Provides local employment, manages decentralized value addition and produces finished goods.
Startups	Bring technology and design for conversion processes.	Introduces efficient, scalable and modern methods for waste conversion and product innovation.

How an ODOP - CBC Creates Rural Livelihood Opportunities**Waste-to-Wealth Micro & Small-enterprises**

The synergy of ODOP and the CBC is a direct catalyst for rural livelihood generation. It achieves this by creating numerous waste-to-wealth Micro & Small-enterprises (MSEs). These MSEs focus on decentralized conversion of ODOP-related crop residues into high-value products like bio-fertilizers/pesticides, bio-packaging or specialty chemicals. This model not only converts agricultural liabilities into new revenue streams but also fosters local entrepreneurship, providing consistent employment and income for Self-Help Groups (SHGs) and local youth within the district. Examples of enterprises generated; leaf plates and bio-based packaging, biochar-based soil nutrient enhancers, compost and microbial consortia, essential oil extraction, dehydrated powder units, bio-polymers from starch/ligno-cellulosic biomass, fodder blocks.

Pollution reduction

Residue burning, waste dumping and methane generation can be reduced significantly. Literature from India and Europe confirms 30 - 70% emission reduction through circular waste management (Discover Applied Sciences, 2025).

Local Job Creation: 15-50 jobs per cluster under/as technical operators, collection and logistics, processing workers, marketing and sales, lab technicians and machine operators etc.

Invigorated Soil Fertility

Returning compost, biochar and slurry improve soil structure, texture, organic carbon and crop productivity. Chembioagro (2020) shows 8-20% yield improvement under biochar-amended soils.

Pathways for Common ODOP Commodities

Common ODOP commodities can be strengthened through a stepwise approach that any district can adopt. Starting with improved production practices, quality standards and farmer collaboration via FPOs/SHGs/cooperatives, districts can then introduce small processing units for value addition. Simple branding, local market linkages and participation in fairs enhance visibility, while connecting producers to retail chains, online platforms and institutional buyers ensures steady demand. This pathway transforms raw produce into market-ready goods, boosting income and employment.

**Technology Integration in CBC**

Category	Technologies / Tools
Digital Tools	Blockchain for traceability AI for residue mapping IoT-enabled composting units Mobile apps for FPO/SHG value-chain management Drone monitoring for crop and residue management Data analytics platforms for yield and waste optimization GIS mapping for resource and waste management
Processing Technologies	Pyrolysis for biochar Anaerobic digestion Dehydration units Cold-press extraction Fermenters Solar dryers for crop residues Pelletization units for organic waste Enzymatic treatments for waste valorization

Category	Technologies / Tools
Waste Collection Systems	FPO-led aggregation SHG-operated decentralized units Community composting hubs Door-to-door collection services Smart bins with IoT sensors for segregation and tracking

Policy Alignment and Funding Advantage

CBCs align with PMFME (ODOP), National Bio-economy Strategy (DBT), PMKSY food processing infra, NABARD Producer Enterprise Models, CSR focus on sustainability, waste management, green livelihoods, SDG 1, 2, 8, 12, 13. Therefore, funding agencies prefer integrated models that combine livelihood, climate action, entrepreneurship and women-led business units.

Conclusion

The **ODOP-Circular Bio-economy Cluster** represents a futuristic, sustainable and community-driven rural development model. By aligning district specialization (ODOP) with biomass utilization, local entrepreneurship, scientific waste valorization and FPO-SHG participation, India can transform agriculture into a regenerative, zero-waste and high-income ecosystem. This model is not just economically promising- it is essential for a climate-resilient, resource-efficient and livelihood-rich rural India.

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SHELF LIFE EXTENSIONS: ADVANCES IN FOOD PRESERVATION TECHNIQUES

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Abstract

According to the Food and Agriculture Organization (FAO), one-third of all food produced globally is lost or wasted, making the development of advanced preservation techniques a critical priority for global food security and environmental sustainability. While traditional methods such as canning and freezing are effective, they often compromise the nutritional quality and sensory attributes of food products. This paper examines the shift from conventional methods to novel preservation technologies that prioritize "fresh-like" quality and minimal processing.

Key innovations discussed include non-thermal methods such as high-pressure processing (HPP), pulsed electric fields (PEF), and cold plasma, which inactivate pathogens without the detrimental effects of high heat. Furthermore, this article explores the protective capabilities of nanotechnology-based coatings and modified atmosphere packaging (MAP), as well as the growing trend of biopreservation using natural antimicrobials. Despite challenges related to higher implementation costs and regulatory approvals, these advancements represent a significant shift towards a more sustainable food supply chain. By reducing waste and enhancing safety, these technological milestones are poised to redefine the future of food manufacturing and consumer health.

Keywords: Food preservation, Innovative technologies, Shelf-life extension, Non-thermal processing, Food waste reduction, Sustainable food systems.

Introduction

Food preservation refers to the processes and techniques used to prevent food from spoiling, extending its shelf life, and also avoiding microbial contamination or food poisoning. Food preservation is essential to reducing waste, ensuring food security, and maintaining nutritional value. Traditional preservation methods, for example, freezing, refrigeration, pasteurization, fermentation, and canning, have some limitations. Advanced technologies provide new solutions to enhance food quality, extend the shelf life of food, and minimize environmental impact.

But why is food preservation so important?

According to the United Nations Food and Agriculture Organisation (FAO), one-third of all food produced globally is lost or wasted. This not only has significant economic and environmental implications, but it also affects food security and sustainability.

In this article, we will explore the latest advances in food preservation techniques and their benefits, and also their potential to transform the food industry. From improving food safety to extending shelf life, we will explore the world of food preservation and discover how science and technology are helping to reduce food waste and create a more sustainable food future. The continued innovation in food preservation will play a vital role in shaping a more sustainable food future.

Traditional Food Preservation Methods

Time-tested food preservation methods like heat treatment, canning, freezing, and drying have been employed for centuries. Although effective, these conventional techniques can degrade the nutritional content, texture, and taste of preserved foods. Furthermore, they may not provide adequate protection against spoilage and contamination, especially for perishable items.

Food Preservation Techniques

Certain innovative preservation techniques have shown acceptable results, are mentioned below:

1. Modified Atmosphere Packaging (MAP):

In Modified Atmosphere Packaging (MAP), spoilage is prevented, and shelf life is extended by maintaining a carefully controlled gaseous environment around the food. This involves regulating the proportions of gases such as oxygen, nitrogen, and carbon dioxide within the package. According to Opara et al. (2019), actively managing this gas composition, particularly by replacing oxygen (O_2) with nitrogen (N_2) or carbon dioxide (CO_2), is crucial for suppressing microbial activity and slowing oxidative processes.

Benefits: The benefits of MAP include a longer product lifespan, improved texture, decreased spoilage, and better retention of original freshness.



Figure (1) Modified Atmosphere Packaging (MAP)

2. Nanotechnology–Based Coatings:

This technique uses edible coatings and films, often enhanced with nanoparticles or other natural polymers, to regulate the movement of moisture and oxygen (Kondle et al. 2024). These thin, protective layers, derived from natural sources such as cellulose, starch, or proteins, are applied directly to food surfaces. Their primary functions are to prevent moisture loss, manage gas exchange, and provide a physical barrier against contaminants. Some advanced versions can also incorporate antimicrobial agents or antioxidants.

Benefits: These coatings contribute to better food safety, offer superior protection against gases and moisture, decrease the reliance on conventional synthetic packaging, and can even improve the visual appeal of fresh produce.

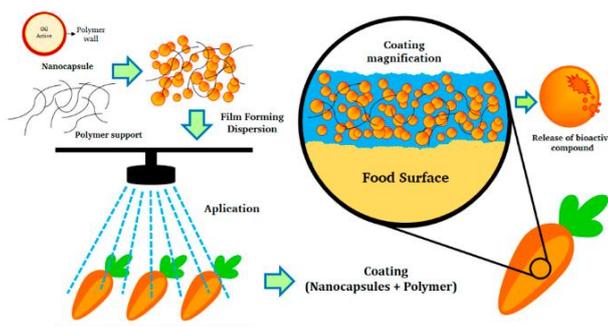


Figure (2) Nanotechnology–Based Coatings

3. Pulsed Electric Field (PEF) Technology:

Transforming food preservation, Pulsed Electric Field (PEF) technology introduces an innovative, non-thermal method. It operates by sending short, intense electrical pulses through liquid and semi-liquid foods. The resulting electric field causes critical damage to the cell membranes of bacteria and other microorganisms, thereby inactivating them. According to Syed et al. (2017), this effectively eliminates the unwanted microbes and preserves the food with negligible heat-induced alterations.

Benefits: Nutrients are preserved, the product retains its fresh characteristics, energy consumption is lower than in thermal processing, and heat-sensitive components experience minimal damage.

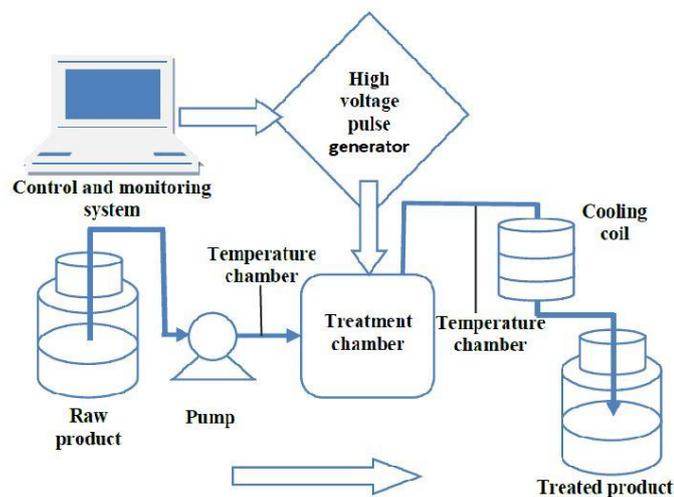


Figure (3) Flow chart of a PEF food processing system with basic components

4. High Pressure Processing (HPP):

HPP is a non-thermal food preservation technique that uses extremely high hydrostatic pressure (typically 100-600 MPa) to kill harmful bacteria, molds, and yeasts, thereby extending shelf life and inactivating spoilage microorganisms (W/giorgis, 2019). HPP is commonly used to preserve juices, smoothies, deli meats, seafood, and other ready-to-eat beverages and foods. By using HPP, food manufacturers can create safe, flavorful, and nutritious products that meet the demand of today's consumers for fresh-like quality.

Benefits: Preserved texture, nutrients, and fresh flavor; significantly reduced need for chemical additives; and enhanced food safety.

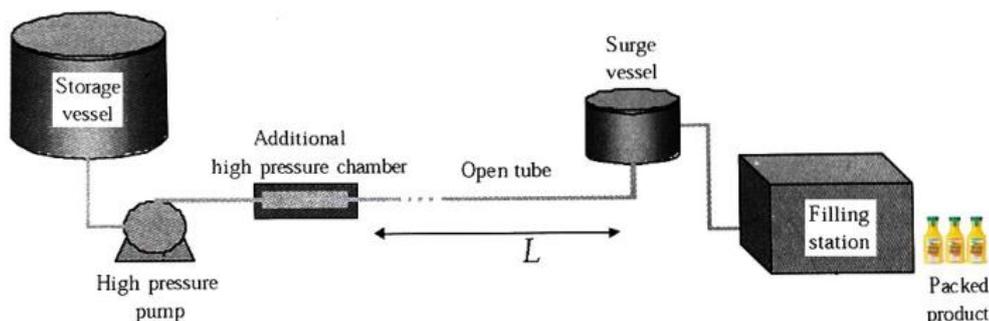


Figure 4: Continuous high-pressure processing system

5. Cold Plasma Technology

This non-thermal preservation technique generates ionized gas (plasma) at low temperatures, applying it to food surfaces or packaging. The reactive components within this plasma, such as reactive oxygen and nitrogen species, interact directly with the cell walls of microbes, causing their inactivation. This method is particularly beneficial for surface decontamination of heat-sensitive foods like fresh produce, as it has a minimal impact on food quality and provides a chemical-free sterilization solution (Bourke et al., 2018).

6. Pulsed Light Technology

This technique involves exposing the surfaces of food or packaging materials to brief, **high-intensity bursts of broad-spectrum light** (including UV, visible, and infrared wavelengths). The powerful light energy works by disrupting the DNA and cell membranes of microorganisms, leading to their rapid inactivation. Benefits include fast and effective surface sterilization, a chemical-free treatment, and suitability for a wide variety of solid food products and their packaging.

7. Biopreservation with Natural Antimicrobials

This approach harnesses naturally occurring antimicrobial compounds to suppress the growth of spoilage organisms and pathogens.

- **Bacteriocins:** These are peptides produced by specific bacteria (e.g., nisin from *Lactococcus lactis*) that inhibit the growth of other bacteria, including those responsible for spoilage or disease. Nisin, for example, is commonly used in dairy products and processed meats.
- **Protective Cultures:** This involves intentionally adding beneficial microorganisms (like certain lactic acid bacteria) to food products (Sionek et al., 2024). These cultures then compete with spoilage organisms for nutrients or produce antimicrobial substances such as organic acids, hydrogen peroxide, or bacteriocins themselves.
- **Natural Antioxidants:** Extracts derived from plants (e.g., rosemary, green tea, grape seed) are utilized to prevent oxidative spoilage, particularly in fats and oils, thereby extending the shelf life of items like baked goods, meat, and snacks.

The advantages of biopreservation include its appeal for "clean label" products, a reduced need for synthetic additives, and its support for natural preservation processes.

8. Advanced Thermal Treatments

While heat treatment is a traditional method, newer approaches are optimizing its application for better results:

- **Ohmic Heating:** This method involves passing an alternating electric current directly through the food, which generates rapid and uniform internal heating. This leads to shorter processing times and better retention of the food's nutritional content and sensory qualities.
- **Microwave-Assisted Thermal Sterilization (MATS):** This technique combines microwave energy with conventional heating to achieve rapid and uniform sterilization. It is especially effective for ready meals that contain particulates.

Both ohmic heating and MATS offer faster processing times, improved quality retention compared to conventional sterilization methods, and enhanced energy efficiency.

Limitations of Innovative Preservation Techniques:

While highly promising, these advanced technologies are not without their challenges:

- **High Initial Investment:** Implementing new food preservation technologies (e.g., HPP, PEF equipment) can be expensive, posing a barrier for small and medium-sized enterprises.

- **Scale-Up Challenges:** Some techniques may not be easily scalable or cost-effective for very large-scale food production or for certain food matrices.
- **Consumer Acceptance and Perception:** Novel food preservation techniques may raise concerns among some consumers who prefer "minimally processed" or traditionally preserved foods, requiring clear communication and education.
- **Limited Applicability for Certain Foods:** Not all technologies are universally applicable to all food types (e.g., PEF is best for liquids, HPP for high-moisture foods).
- **Regulatory Hurdles:** Gaining regulatory approval for new technologies and materials (especially smart packaging components) can be a lengthy and complex process.

Conclusion

As we all know that the global food preservation market continues to grow, and the adoption of these innovative techniques will play an important role in ensuring food security, reducing waste, and promoting sustainable agriculture practices. New ways to keep food fresh are being discovered. These methods, like special electric fields, high pressure, and new packaging, are changing the food industry.

These new techniques will help make food safer, healthier, and better for the environment. People will be able to eat fresh and nutritious food all year round. Food companies will also benefit. They will waste less food, use less energy, and produce food more efficiently. This is good news for the planet. As these new methods become more widely used, the food industry will change for the better. People will have access to healthier food, and companies will be more efficient and environmentally friendly. Future research and industry collaboration will drive the development of even more effective and efficient preservation methods, shaping the future of food preservation. The future of food looks promising.

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DESTRUCTIVE FISHING: CAUSES, CONSEQUENCES, AND CONTROL MEASURES

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Abstract

Wild capture fisheries are a cornerstone of the global food supply, harvesting resources from biologically diverse ocean ecosystems to sustain billions of people. Marine fisheries have shown remarkable growth, increasing production from 5.34 lakh tonnes in 1950–51 to 44.95 lakh tonnes in 2023–24, with global per capita consumption rising from 9.1 kg in 1961 to 20.7 kg in 2022. Fisheries and aquaculture support the livelihoods of around 600 million people, with small-scale fisheries providing 40% of global catch and employing approximately 60 million individuals, particularly in coastal and island communities. Despite traditional knowledge and sustainable indigenous fishing practices, destructive fishing practices such as blast fishing, cyanide fishing, bottom trawling, muro-ami, ghost fishing, and the use of poisonous plants persist, causing irreversible habitat damage, biodiversity loss, and depletion of fish stocks. Aligning management strategies with SDG 14, strengthening enforcement, and promoting sustainable alternatives are critical to safeguarding marine ecosystems, supporting fisheries-dependent communities, and ensuring long-term food security.

Keywords: Destructive fishing practices, Habitat damages, Effect fishermen, Control measure

Introduction

The global food supply depends heavily on wild capture fisheries, which harvest resources from rich and biologically diverse ocean environments to sustain billions of people. The marine fisheries sector has demonstrated remarkable growth over the decades, with production increasing from 5.34 lakh tonnes in 1950-51 to an impressive 44.95 lakh tonnes in 2023-24. global per capita annual consumption rising from 9.1 kg in 1961 to 20.7 kg in 2022. Marine capture fisheries produced 79.7 million tonnes in 2022. Fisheries and aquaculture support the livelihoods of about 600 million people globally, many of whom live in coastal zones and on islands where fishing resources are especially important. Accounting for 40% of global catch and employing around 60 million people, small-scale fisheries are essential to coastal communities. Ensuring sustainability in fisheries would help secure livelihoods, protect ecosystems, and preserve the cultural and spiritual significance of marine resources. Fishing techniques for wild fish are primarily determined by an understanding of species behaviour, habitat characteristics, and environmental features.

Indigenous fishing gears were developed by traditional fishers drawing on their deep, experience-based knowledge of nature. The persistence of harmful fishing methods remains a serious issue, as their eradication has proven difficult even with government involvement. SDG 14 *Life Below Water*

is one of the most important global policy frameworks for fisheries management, especially through Targets 14.4 and 14.6. Collectively, these targets focus on regulating harvesting, eliminating harmful subsidies, and addressing overfishing, IUU fishing, and destructive fishing practices. Nevertheless, the absence of a recognized indicator for destructive fishing hampers efforts to monitor progress and undermines its effectiveness as a policy term. Destructive fishing practice (DFP) is one which results in direct damage to either the fished habitat or the primary habitat structuring organisms in the fished.

Destructive fishing can be defined as fishing activities that cause irreversible harm to marine habitats, significantly disrupt ecosystems, lead to unsustainable population declines, and adversely affect the wellbeing of dependent communities. It poses one of the most serious threats to thriving wildlife and healthy oceans. There are many types of destructive fishing practices, which are described below: blast fishing, bottom trawlers, cyanide fishing, electrofishing, ghost fishing, illegal fishing, muro-ami fishing, the use of poisonous plant materials, trap fishing, traps and pots, and the use of underwater breathing apparatus.

Blast fishing

Blast fishing or dynamite fishing involves detonating explosives in the water to disable or kill schools of fish, causing widespread environmental damage. Ammonium nitrate and dynamite are frequently utilized as explosive materials in dynamite fishing. The type of explosive has shifted over time from commercially manufactured dynamite to improvised devices made from kerosene and fertilizer packed into beer bottles, but the fundamental method has remained unchanged. More than 25 years ago, Alcala and Gomez (1979) estimated that restoring just 50% of coral cover to pre-blast levels would require approximately 40 years. Schools of reef fish are first identified visually, then the fishing boat approaches to within about five meters and ignites and throws the bomb into the center of the school. Once the explosion occurs, fishermen dive into the water to gather fish that have been killed or temporarily stunned by the shock wave. Rising export opportunities and the rapid development of hotels and restaurants have led dynamite fishers to concentrate on commercially important reef fishes, including groupers, rabbitfish, snappers, and fusiliers. Blast fishing causes widespread ecological damage, destroying coral reefs, degrading reef habitats, and weakening barriers that normally protect coastal areas from storm surges. This illegal fishing method most widely and persistently used in parts of southeast asia (Indonesia, Philippines, Malaysia, Myanmar), east Africa (Tanzania, Kenya) and Lebanon.



<https://blog.nus.edu.sg/nomadchronicles/2020/09/02/is-eco-tourism-the-solution-in-saving-our-oceans/>

Bottom- trawlers

Bottom trawling is among the most destructive fishing techniques and accounts for as much as half of all discarded marine life worldwide. It unintentionally captures many non-target species, including fish, turtles, seabirds, and marine mammals, and many of these animals die as a result. Side-by-side comparisons reveal that spot prawn bottom trawls generate nine times more bycatch than selective gear types. Fish that are “unwanted” and discarded by the bottom trawler are often juveniles of valuable species caught by other fishermen. Bottom trawling often leads to overfishing because the gear is not selective and discards a lot of dead fish. Overfishing by bottom trawls is a direct threat to local fishing communities and to tourism from sport fishing. The most definitive evidence connects bottom trawling to bycatch impacts and harm to seafloor ecosystems. Bycatch impacts are due to its highly non-selective nature in comparison to almost every other gear except gillnets. Seabed habitat impacts are largely unique to bottom contact gears, with bottom trawls and dredges ranking highest among fishing gears in terms of these impacts. It is commonly acknowledged that bottom trawling is “the most widespread source of anthropogenic physical disturbance to global seabed habitats.” Bottom trawling has been banned in many different locations worldwide: Indonesia, US (Florida, Georgia, North Carolina, and South Carolina), Azores, Madeira, Canary Islands, New Zealand, Mediterranean (Europe and North Africa). Bottom trawling can significantly harm the seafloor and the habitats that sustain marine life. The heavy fishing equipment dragged along the seabed can destroy fragile ecosystems, including deep-sea corals, sponges, and other organisms that live on or in the ocean floor. By removing large numbers of marine species, trawling upsets natural ecosystem balance, often causing declines in both targeted species and the predators that rely on them, which can trigger cascading effects throughout the food web. Because deep-sea ecosystems recover very slowly, the damage caused by trawling can last for decades or even centuries. Many deep-sea species grow and reproduce at extremely slow rates, making population recovery difficult or sometimes impossible. In addition to biological damage, trawling disturbs seabed sediments, releasing stored carbon into the water and atmosphere. This process not only contributes to climate change but also reduces the ocean’s capacity to store carbon by destroying habitats that play a role in carbon sequestration.



Marine Conservation Society (MCS) of an area of seabed damaged by trawling.

Cyanide fishing

Cyanide fishing is one of the most destructive techniques used for catching live fish. This practice is illegal in many countries, fishers squirt concentrated sodium cyanide onto reefs to stun fish and scoop them up for the aquarium trade or the live food fish market. But cyanide is indiscriminate: it often kills the fish, and can kill corals and other reef organisms in the process. Cyanide (locally referred to as drugs) is the gear of choice in three main fisheries: ornamental fishes, live reef food fishes (mostly grouper and Napoleon wrasse), and rock lobsters (*Panulirus* spp.).



uses sodium cyanide to hunt for fish. (Photo by WILDLIFE GmbH/Alamy Stock)

In each of these fisheries, the basic technique involves divers, often supported by hookah, using bursts of cyanide solution from squirt bottles to stun their targets. Cyanide use begins with breaking down large tablets and placing them into plastic detergent containers. Once dissolved, the hydrocyanic acid (HCN) is employed by collectors to incapacitate ornamental fish and kill food fish. When collectors swim toward the reef, fish typically hide among the coral structures. Collectors prevent fish from escaping by spraying hydrocyanic acid solution onto the coral head. Over the course of the dive, the solution becomes diluted, making concentration control difficult. Consequently, about half of the exposed fish die, while the others become confused and swim away. Some stunned fish are picked up from the seabed, while others are caught in gill nets. In total, only about 10% of the exposed fish are selected, mainly those with bright coloration attractive to aquarists.

Electro fishing

Electrofishing, the use of electric fields in water to capture or control fish. Electric stickers are used for fishing at high level regions. The equipment includes a generator, an anode, a cathode, a landing net, and electrical connections. The generator, which produces the current, is placed on shore, in a boat, or carried by the fisherman. The cathode is kept near the generator or dragged behind. The fisherman operates the anode while moving through the water, causing fish within its range to become immobilized and easily collected using a net or by hand. Electrofishing is a widely used and inexpensive sampling method, but it poses risks to both target and non-target organisms. Electric current induces convulsions, erratic movement, and unconsciousness in fish, allowing fishers to capture them easily. Larger fish and broodfish are most commonly caught using this method. Long-term use of these techniques in water bodies can cause the death of many unintended species, including snakes, frogs, turtles, and other animals.



Source: Devarshi Ranjan et al, 2023

Ghost fishing

Ghost fishing is the term used for fishing gear that has been lost or left behind and continues to catch fish. It is harmful to the environment because the fish caught are not used and are wasted. The issue was first raised at the 16th Session of the FAO Committee on Fisheries in April 1985. Ghost nets are one of the most harmful forms of marine pollution, as they continue to capture marine life while also posing hazards to navigation. Fishing gear and other debris that settle on the seabed or shorelines present a serious threat to marine organisms, especially when pieces of nets are swallowed and remain trapped in the digestive system. This debris originates from human actions and natural causes. Ghost fishing normally occurs with passive fishing gear such as longlines, gill nets, entangling nets, trammel nets, traps and pots, etc. as opposed to active fishing gear such as trawls and seines. In passive fishing methods, ghost fishing becomes a major concern because the capture mechanism depends on the movement of target species. It affects both target and non-target organisms and does not remain confined to one place. This allows ghost fishing to impact numerous species over broad areas and at different depths. Additionally, fishing gear designed for specific species or size ranges increases the risk for certain species.



An olive ridley turtle entangled and shark killed in ghost gear ©Alex Mustard.

MURO-AMI

Muro-ami is a type of drive-in net fishing technique whereby a line of fishermen in the water use scare-lines (typically a line with pieces of sheet or plastic tied off at regular intervals, with a weight on the end) to drive fish down a reef towards a bag net. The scare lines are rhythmically lifted and dropped into the reef framework, often breaking live corals while the fish are driven ahead. Reef damage is caused by the scare lines weights hitting fragile coral. In the Philippines, commercial muro-ami fishing involves hundreds of swimmers—usually between 200 and 300—each using a scareline, and primarily captures schooling herbivorous and planktivorous species from the Acanthuridae and Caesionidae families. Because muro-ami severely damages coral reefs and depletes fish populations, protests from various sectors emerged, drawing attention to the dangers of this destructive fishing practice. To replace the destructive muro-ami method, the Philippine Bureau of Fisheries and Aquatic Resources proposed *pa-aling*, a modified fishing gear that uses bubbles supplied through plastic hoses to drive fish into a set net.



Muro-ami fishing is destructive to coral reefs (Image courtesy of the Wildlife Conservation Society)

Plant Poison

It is an ancient fishing method which is effective in rock pools and small, semi-enclosed areas. Even though it was mainly used in freshwater, Australian Aborigines and Californian Indians also used this method in saltwater to catch octopus, shellfish, and fish stuck in intertidal pools. Most fish poisons, or ichthyotoxins, originate from related plant species and contain chemicals that stun fish through the gills or ingestion, causing them to rise to the surface for capture. The poison was made by crushing parts of certain plants and putting them into the water. This was usually done in still or slow-moving water so the poison would not wash away. Fish were then collected by hand or sometimes with baskets, spears, or nets. Local people use this method of fishing owing to two reasons; firstly, trees, shrubs or herbs which can be used for this purpose are easily available at riparian areas. Secondly, fishes killed by these plant poisons are said to be harmless for human consumption. The two primary chemicals that occur in most plants used for stunning fish are saponin and rotenone. Plant toxins affect both target and non-target species, causing widespread damage to aquatic ecosystems. Poisoning spreads downstream, leading to extensive losses of juvenile fish, which supports the need for a strict ban on the use of plant poisons in all aquatic resources.



Source: Poison fishing using Mongonbo (Takanori Oishi, 2017)

Trap and Pots Fishing

Trap fishing is one of the oldest fishing methods and is widely practiced in tropical and temperate seas worldwide. The unique design of pots and traps encourages aquatic organisms to enter but makes escape difficult, and these designs are generally traditional and vary depending on location. Because traps and pots are connected to surface buoys by vertical lines, they pose a serious entanglement risk to sea turtles and marine mammals. Leatherback turtles and large whales, such as North Atlantic right whales and humpback whales, are especially affected due to their movement patterns and feeding behaviour. Entanglement can result in injuries or drowning when heavily weighted gear prevents animals from surfacing. In the Canada where 'ghost fishing' was simulated with traps targeting Dungeness crab, it was estimated that losses due to ghost fishing accounted for seven percent of the total landings.



Traditional trap (Common Koodu)



Trap and pots (Photo by David Hills of @FishyPictures)

(Souce: Mathews Plamoottil *et al.*, 2017)

Damage caused by destructive fishing activities

The marine ecosystem and the livelihoods of Northern Province small-scale fishers are greatly affected by irresponsible fishing activities. The nature and intensity of these impacts are determined by the particular destructive fishing methods applied by the fishers. Ddestructive fishing often damages benthic habitats and results in non-selective fishing mortality. Unregulated and increased application of destructive fishing practices results in the sudden decline of target fish populations and other ecologically valuable marine organisms such as turtles, sharks, seals, whales, and dugongs. These practices may also cause phenotypic modifications and alter species dominance, including the shift of fringing coral reefs from coral-dominated to algae-dominated systems as a result of overfishing key herbivorous fish and invertebrate species. Destructive fishing methods lead to significant biodiversity decline, destabilization of marine food chains, increased extinction of endangered species, unsustainable harvesting of commercial fish stocks, and irreversible contamination of marine environments. Local fishermen have reported physical injuries while defending their fishing nets against damage by Indian vessels and during times when they remained ashore due to the threat posed to their fishing gear. Loss of coral reef and mangrove ecosystems weakens the tourism potential of coastal regions and directly affects the economic performance of the hotel industry. The destructive fishing practices affect the economy of country. Trawlers can severely damage the drift nets and small boats of local fishermen, especially at night when the

extended and nearly invisible gillnets commonly deployed by local fishers go unnoticed by trawl vessels.

Legal Reform Options for Destructive Fishing Control

There is a need to increase and revise penalties for offences under the Fisheries Act of 1973 and its amendments, since the current level of punishment fails to deter destructive fishing activities. The prospect of high profits encourages offenders to continue illegal fishing practices despite the risk of penalties. Each state of the world has sovereign right to manage their exclusive economic zones. Alongside penalties for destructive fishing, socially responsible projects should support fishing communities by providing education, training, self-employment, and equal opportunities.

Conclusion

Destructive fishing methods—including dynamite, cyanide, muro-ami, plant poison, trap fishing and ghost fishing are still commonly employed in many countries. They pose serious threats to coral reefs, vital habitats for reef fish, and compromise the livelihoods of small-scale fishers. Although legal frameworks exist, inadequate enforcement has allowed these practices to continue. Strengthening the implementation of laws at both local and national levels is therefore recommended to mitigate this issue. Environmentally responsible practices, such as spearfishing and line fishing, offer sustainable alternatives that safeguard marine ecosystems.

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PROCESSING OF APPLE INTO VALUE-ADDED PRODUCT: APPLE SQUASH

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Abstract

Apple is a highly perishable, important temperate fruit, which leads to considerable post-harvest losses. Processing apples into value-added products, such as apple squash, helps reduce wastage, extend shelf life, and increase economic returns. Apple squash is a non-fermented beverage prepared by blending clarified apple juice with sugar syrup, citric acid, and permitted preservatives. The processing includes fruit selection, washing, juice extraction, formulation, pasteurization, and packaging. This product retains much of the nutritional quality of fresh apples while providing a convenient and refreshing drink. Thus, processing of apples into squash is an effective method of value addition and post-harvest management.

Introduction

Apple (*Malus domestica*) is one of the most widely consumed temperate fruits due to its pleasant flavor, nutritional value, and availability. Apples are rich in carbohydrates, dietary fiber, vitamin C, and various antioxidants. However, fresh apples are highly perishable and are prone to post-harvest losses due to microbial spoilage and physiological deterioration. Processing apples into value-added products such as apple squash helps in extending shelf life, reducing post-harvest losses, and increasing market value. Apple squash is a concentrated fruit beverage prepared by mixing clarified apple juice with sugar syrup, acidulants, and preservatives. It is diluted with water before consumption and is popular for its refreshing taste and nutritional benefits. This live project was undertaken to study the processing technique of apple squash, understand the role of ingredients and preservation methods, and evaluate the quality of the final product.

Materials and Methods

Raw Material: Fresh ripe apples

Ingredients:

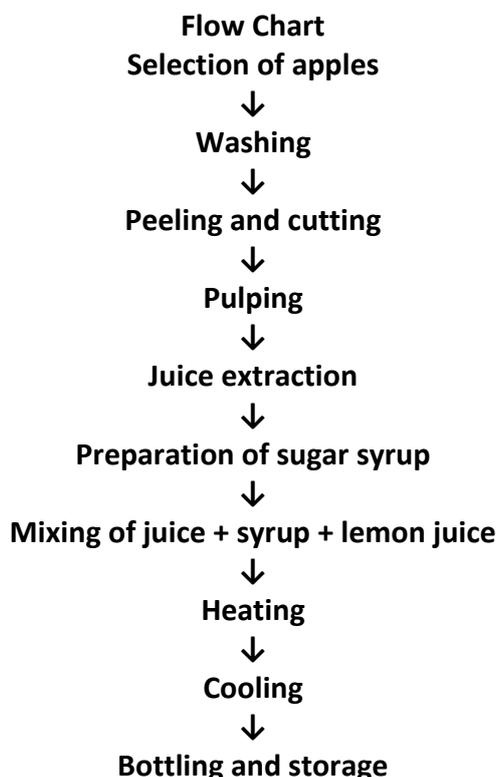
- Sugar
- Lemon juice (for acidity and preservation)
- Water

Equipment Used:

- Knife
- Cutting board
- Mixer/Grinder
- Muslin cloth or sieve
- Pan
- Spoon
- Measuring jar
- Glass jars for storage

Procedure

- Step 1:** Selection and Washing: Fresh, ripe, and sound apples were selected. The fruits were thoroughly washed with clean water to remove dirt and surface contaminants.
- Step 2:** Peeling and Cutting: Apples were peeled and cut into small pieces after removing seeds and core.
- Step 3:** Juice Extraction: The apple pieces were crushed using a mixer/grinder to obtain pulp. The pulp was filtered through a muslin cloth to extract clear apple juice.
- Step 4:** Preparation of Sugar Syrup: Sugar and water were heated in a pan until the sugar completely dissolved, forming a clear syrup. The syrup was cooled to room temperature.
- Step 5:** Mixing: Apple juice was mixed with the prepared sugar syrup. Lemon juice was added to enhance flavor, maintain acidity, and act as a natural preservative.
- Step 6:** Heating: The mixture was gently heated for a few minutes with continuous stirring to ensure uniform mixing and improve shelf life. Over-boiling was avoided.
- Step 7:** Cooling and Bottling: The prepared apple squash was cooled and filled into clean, dry glass jars. Jars were tightly sealed and stored in a cool place.



Role of Ingredients

Apples: Provide natural flavor, nutrients, and body to the squash.

Sugar: Acts as a sweetening agent and also helps in preservation by reducing water activity.

Lemon Juice: Acts as a natural preservative, maintains acidity, improves taste, and prevents microbial growth.

Storage

The prepared apple squash was stored in clean glass jars. It can be stored for several weeks under refrigeration. Proper sealing and hygiene increase shelf life.

Result and Observation

The prepared apple squash had a pleasant aroma, attractive color, and sweet-tangy taste. On dilution with water, it produced a refreshing beverage. No signs of spoilage were observed during the storage period.

Conclusion

The live project successfully demonstrated the processing of apple into a value-added product in the form of apple squash. This method helps in reducing post-harvest losses, increasing shelf life, and providing an opportunity for small-scale entrepreneurship. The use of lemon juice as a natural preservative makes the product safer and economical.

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PRODUCTION OF MILLET- BASED VALUE-ADDED PRODUCTS FOR NUTRITIONAL ENHANCEMENT

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Abstract

Milletts are nutrient-dense, climate-resilient grains that offer significant potential for nutritional enhancement through value addition. Compared to commonly consumed cereals such as rice and wheat, millets possess higher levels of dietary fiber, essential minerals, antioxidants, and bioactive compounds. The production of millet-based value-added products—such as bakery items, instant mixes, snacks, and malted foods—enhances nutrient bioavailability, improves sensory qualities, and increases consumer acceptance. Processing techniques like germination, fermentation, and extrusion further reduce anti-nutritional factors and improve digestibility. Millet-based value-added products provide superior health benefits, including better glycemic control, improved gut health, and reduced risk of lifestyle diseases. Their incorporation into modern diets supports nutritional security, sustainable agriculture, and economic empowerment, making them a healthier and more sustainable alternative to conventional cereal-based products.

Introduction

Milletts are a group of small-seeded cereal crops known for their resilience to harsh agro-climatic conditions and superior nutritional profile. Major millets (sorghum, pearl millet) and minor millets (finger millet, foxtail, little, kodo, barnyard, proso) are rich in dietary fiber, minerals, vitamins, and bioactive compounds. Despite their nutritional superiority, millet consumption has declined due to changing food habits and preference for refined cereals. Value addition through processing and product development offers an effective strategy to enhance their nutritional quality, palatability, shelf life, and consumer acceptance.

Materials and Methods

Raw Material: Sorghum, pearl millet, roasted chickpea, peanuts

Ingredients:

- Jaggery, Ghee, Salt, Sand, Cardamom powder

Equipment Used:

- Mixer/Grinder
- Sieve
- Pan
- Spoon
- Jars for storage

Procedure for making Ladoo

Step 1: Roast sorghum, pearl millet and nuts on low flame

Step 2: Mix roasted flours nuts and seeds

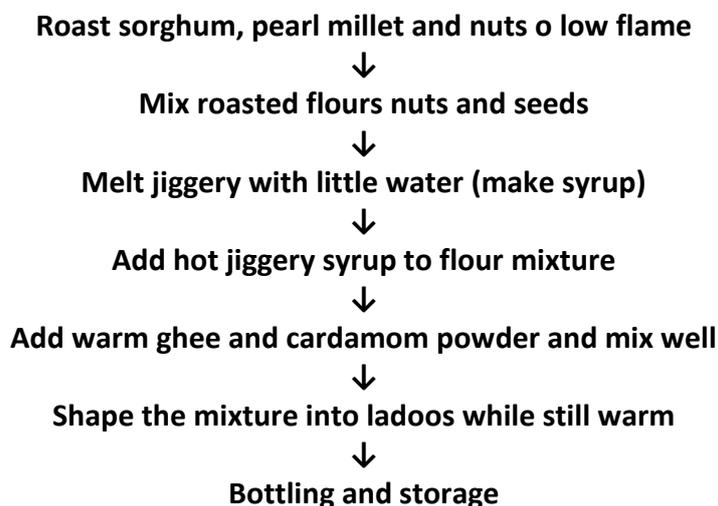
Step 3: Melt jaggery with little water (make syrup)

Step 4: Add hot jiggery syrup to flour mixture

Step 5: Add warm ghee and cardamom powder and mix well

Step 6: Shape the mixture into ladoos while still warm

Flow Chart



Nutritional Importance of Millets

Millets are often referred to as “nutri-cereals” because of the following attributes:

- High dietary fiber (especially finger millet and little millet)
- Rich in minerals such as iron, calcium, zinc, and magnesium
- Low glycaemic index (GI), suitable for diabetics
- Gluten-free, beneficial for celiac patients
- Presence of antioxidants and phenolic compounds

Need for Value Addition

- Improves taste, texture, and appearance
- Reduces anti-nutritional factors (phytates, tannins)
- Enhances bioavailability of nutrients
- Extends shelf life
- Increases market demand and farmer income
- Promotes millet consumption among urban populations

Role in Food and Nutritional Security

- Supports nutrition-sensitive agriculture
- Addresses micronutrient malnutrition
- Promotes climate-resilient food systems
- Aligns with national initiatives like International Year of Millets (2023) and Poshan Abhiyan

Millet Advantage in Value-Added Foods

Millet-based value-added products are considered superior to cereal-based products because millets are richer in dietary fiber, essential minerals such as iron, calcium, and zinc, and bioactive compounds compared to commonly consumed cereals like rice and wheat. Millets have a lower glycemic index, which supports better blood sugar control and helps in preventing lifestyle disorders such as diabetes and obesity, whereas refined cereals are rapidly digested and mainly provide

energy. Most millets are naturally gluten-free, making them suitable for individuals with gluten intolerance, unlike wheat-based cereal products. Processing techniques used in value addition, such as germination, fermentation, and malting, further improve the digestibility and nutrient bioavailability of millets by reducing anti-nutritional factors. In addition to nutritional advantages, millets are environmentally sustainable as they require less water and fewer agricultural inputs than cereals, making millet-based value-added products a healthier and more sustainable alternative.

Conclusion

Millet-based value-added products play a vital role in enhancing nutritional quality while meeting consumer demand for healthy, convenient foods. Adoption of appropriate processing techniques and product diversification can significantly improve millet utilization, contributing to better health, farmer livelihoods, and sustainable food systems.

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USE OF PLANT-BASED PRESERVATIVES IN POSTHARVEST DISEASE CONTROL

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Abstract

Postharvest diseases are a major cause of losses in fruits and vegetables, leading to significant economic damage and reduced market quality. Conventional chemical fungicides, though effective, pose concerns related to residue, environmental safety, pathogen resistance, and consumer health. In recent years, plant-based preservatives have emerged as a promising, eco-friendly alternative for postharvest disease control. These natural preservatives, derived from plant extracts, essential oils, and bioactive compounds, exhibit antimicrobial, antioxidant, and antifungal properties. This article discusses the importance, mechanisms, applications, advantages, and limitations of plant-based preservatives in postharvest disease management, with emphasis on practical use and field relevance.

Introduction

Postharvest diseases are a major challenge in the horticulture sector, silently eroding the hard work of farmers and reducing the availability of fresh produce for consumers. Losses occur at multiple stages, during storage, transportation, and marketing, and they not only cut into farmers' incomes but also undermine food security at a national level. Fruits and vegetables, unlike cereals, are highly perishable because of their high moisture content and active metabolism. This makes them particularly vulnerable to microbial spoilage. Pathogens such as *Colletotrichum*, *Penicillium*, *Alternaria*, *Botrytis*, and *Rhizopus* are notorious culprits, causing decay, discolouration, and deterioration of texture and flavour. The impact is not just economic; it also affects consumer confidence, nutritional quality, and the sustainability of food systems.

Traditionally, chemical fungicides have been the frontline defence against these diseases. While effective in reducing decay, their indiscriminate use has raised serious concerns. Chemical residues on fruits and vegetables pose risks to consumer health, while repeated application contributes to environmental pollution and disrupts ecological balance. Moreover, pathogens often develop resistance to these chemicals, making them less effective over time and forcing farmers to use higher doses or stronger formulations. This cycle increases production costs and further damages ecosystems.

Growing awareness among consumers about food safety and the rising demand for residue-free, organically produced food have accelerated the search for sustainable alternatives. In this context, plant-based preservatives have emerged as a promising solution. These natural substances, derived from plant extracts, essential oils, and bioactive compounds, harness the inherent antimicrobial, antioxidant, and antifungal properties of plants. Unlike synthetic chemicals, they are biodegradable, eco-friendly, and generally recognised as safe for human consumption. Their use not only addresses

the problem of postharvest diseases but also aligns with global trends toward sustainable agriculture, organic certification, and environmentally responsible food production.

Plant-based preservatives offer multiple advantages. They can be applied in various forms such as dips, sprays, edible coatings, or fumigation, depending on the crop and storage conditions. Essential oils like clove, cinnamon, thyme, and lemongrass have shown strong antifungal activity even at low concentrations. Extracts from neem, garlic, ginger, and aloe vera have demonstrated effectiveness in reducing spoilage and extending shelf life. Beyond disease control, many of these natural compounds also enhance the nutritional and sensory qualities of produce, making them more appealing to consumers. The adoption of plant-based preservatives represents more than just a technical shift; it is part of a broader movement toward sustainable food systems. By reducing reliance on synthetic fungicides, farmers can lower production costs, protect the environment, and meet consumer expectations for safe, healthy food. At the same time, these practices contribute to reducing postharvest losses, which in turn improves farmer profitability and strengthens national food security.

Understanding Postharvest Diseases: Causes and Impact

Postharvest diseases typically arise due to a combination of factors. Mechanical injuries during harvesting and handling create entry points for pathogens. High humidity and temperature during storage accelerate microbial growth. Poor sanitation, latent infections acquired in the field, and weak postharvest handling practices further exacerbate the problem. The impact of these diseases is both economic and qualitative. Quantitative losses occur through visible decay and spoilage, while qualitative losses include changes in appearance, flavour, and nutritional value. These issues lead to rejection of produce in domestic and export markets, reduced shelf life, and diminished consumer trust. In some cases, postharvest losses can reach up to 30%, especially in highly perishable crops like berries and leafy greens.

Concept of plant-based preservatives

Plant-based preservatives are natural substances extracted from various parts of plants, including leaves, seeds, bark, roots, and rhizomes. These substances have long been used in traditional medicine and food preservation due to their antimicrobial and antioxidant properties. Common sources include neem, tulsi, eucalyptus, mustard, fenugreek, cinnamon, ginger, turmeric, clove, thyme, and lemongrass. Essential oils derived from these plants are particularly potent, often effective at low concentrations. These natural compounds are biodegradable, environmentally safe, and generally recognised as safe for human consumption. Their use in postharvest management represents a shift toward sustainable agriculture and reduced reliance on synthetic chemicals.

Types of plant-based preservatives used in Postharvest management

Plant-based preservatives can be categorised into three main types: plant extracts, essential oils, and plant gums or resins. Plant extracts are obtained using solvents like water or alcohol and contain bioactive compounds such as phenols, flavonoids, alkaloids, and tannins. Examples include neem leaf extract, garlic extract, aloe vera gel, and ginger extract. Essential oils are volatile aromatic compounds extracted from plant parts and include clove oil, cinnamon oil, thyme oil, lemongrass oil, and eucalyptus oil. These oils are highly effective in controlling microbial growth. Plant gums and resins, such as gum arabic and aloe vera, form protective coatings that reduce moisture loss and microbial attack.

Mechanism of action of plant-based preservatives

Plant-based preservatives control postharvest diseases through multiple, complementary mechanisms, making them highly effective and reducing the likelihood of pathogen resistance. Their

antifungal and antibacterial activity is primarily attributed to bioactive compounds such as phenols, flavonoids, terpenoids, alkaloids, and essential oils. These compounds disrupt the integrity of pathogen cell membranes, increase membrane permeability, and interfere with vital enzyme systems. As a result, essential cellular processes such as respiration, nutrient transport, and energy production in pathogens are impaired, leading to inhibition of spore germination, restricted mycelial growth, and eventual cell death. In addition to direct antimicrobial action, plant-based preservatives exhibit strong antioxidant properties. Fruits and vegetables experience oxidative stress during storage due to the accumulation of reactive oxygen species (ROS), which accelerates senescence and tissue breakdown, making produce more susceptible to pathogen attack. Natural antioxidants present in plant extracts scavenge these free radicals, reduce oxidative damage, and slow down ripening and senescence processes. This delay in physiological deterioration indirectly enhances the produce's natural resistance to postharvest pathogens.

Certain plant extracts also function as elicitors of host resistance. When applied to harvested produce, they stimulate the fruit's internal defence mechanisms by activating the synthesis of phenolic compounds, phytoalexins, and defence-related enzymes such as peroxidase, polyphenol oxidase, chitinase, and β -1,3-glucanase. These biochemical changes strengthen cell walls, inhibit pathogen penetration, and limit disease development, thereby reducing decay during storage and transportation. Another important mechanism involves the formation of a physical and semipermeable barrier through plant-based edible coatings. Coatings made from substances such as aloe vera gel, plant gums, starches, or essential oil-infused films cover the fruit surface, reducing oxygen diffusion and moisture loss. Lower oxygen availability slows respiration and pathogen growth, while reduced moisture loss limits tissue softening and cracking that favour infection. At the same time, these coatings act as a protective shield against mechanical injury and microbial invasion. Collectively, the combined action of direct antimicrobial effects, antioxidant protection, induced host resistance, and physical barrier formation enables plant-based preservatives to effectively control postharvest diseases, extend shelf life, and maintain the quality of horticultural produce in a safe and environmentally friendly manner.

Application in different crops

The use of plant-based preservatives has shown promising results across a variety of fruits and vegetables. In mangoes, aloe vera and neem extracts effectively reduce anthracnose and stem-end rot. Apples treated with cinnamon and clove oil show reduced incidence of blue mould. Citrus fruits benefit from thyme and lemongrass oils, which help control green and blue mould. In bananas, plant extracts delay ripening and reduce crown rot. For vegetables, garlic and ginger extracts have been successful in reducing fungal spoilage in tomatoes. Neem-based treatments help prevent storage rots in onions and garlic, while aloe vera coatings extend the shelf life of leafy greens.



Different Preservative delivery methods

Methods of applications

There are several methods for applying plant-based preservatives to postharvest produce. Dipping treatments involve immersing fruits in diluted solutions of plant extracts or essential oils. Spraying is suitable for bulk handling and large-scale operations. Edible coatings incorporate plant extracts into materials like starch or chitosan, which are then applied to the produce. Fumigation uses essential oil vapours in storage environments to control airborne pathogens. Each method has its advantages and can be selected based on the type of produce, scale of operation, and available infrastructure.

Advantages of plant-based preservatives

The benefits of using plant-based preservatives are numerous. They are eco-friendly and biodegradable, posing no threat to the environment. They are safe for consumers and leave no harmful chemical residues. Their compatibility with organic farming practices makes them ideal for sustainable agriculture. Unlike synthetic fungicides, they do not contribute to the development of resistant pathogen strains. Additionally, they help improve the shelf life and quality of produce, enhancing its marketability and consumer appeal.

Limitations and challenges

Despite their advantages, plant-based preservatives face certain limitations. Their effectiveness can vary depending on the crop, pathogen, and environmental conditions. They often have shorter residual activity compared to synthetic chemicals. Standardisation of formulations and application methods remains a challenge. Essential oils can be expensive, and their strong aroma may affect the sensory qualities of the produce. Optimisation of dosage and application techniques is necessary to ensure consistent results. These challenges can be addressed through ongoing research, technological refinement, and farmer training.

Integration with other postharvest technologies

Plant-based preservatives are most effective when integrated with other postharvest technologies. Proper sanitation, cold storage, modified atmosphere packaging, and good handling practices enhance their efficacy. Such integration creates a synergistic effect, providing comprehensive protection against postharvest diseases and extending the shelf life of produce. This holistic approach is essential for modern postharvest management systems.

Role in sustainable and organic agriculture

The use of plant-based preservatives supports the principles of sustainable and organic agriculture. They help farmers meet organic certification standards, reduce environmental pollution, and build consumer trust in safe food. Their adoption contributes to the development of sustainable food systems that prioritise health, ecology, and fairness. As global trends shift toward green technologies, plant-based preservatives are poised to play a central role in future agricultural practices.

Prospects

The future of plant-based preservatives in postharvest disease control looks promising. Research is focusing on nano-formulations of plant extracts, which offer enhanced stability and efficacy. Synergistic combinations of different plant compounds are being explored to improve antimicrobial activity. Efforts are underway to standardise formulations for commercial-scale use. Policy support and incentives can accelerate their adoption among farmers. Advances in formulation technology

will further enhance their shelf life and effectiveness, making them a viable alternative to chemical fungicides.

Conclusion

Plant-based preservatives provide a sustainable, eco-friendly, and consumer-acceptable solution for postharvest disease control. Their ability to reduce decay, extend shelf life, and maintain quality makes them an important component of modern postharvest management. Although challenges related to standardisation and large-scale adoption remain, continued research, effective extension support, and increased farmer awareness can enhance their wider use. When integrated with other postharvest technologies, they significantly reduce losses, improve food safety, and support sustainable development.

Beyond disease control, plant-based preservatives strengthen economic resilience by minimising spoilage, improving marketable yield, and reducing distress sales. They also enhance consumer trust and market access by enabling residue-free and organically acceptable produce, thereby improving price realisation in domestic and export markets. Environmentally, their biodegradable nature reduces chemical pollution and supports climate-smart and biodiversity-friendly agriculture. Additionally, these technologies encourage rural entrepreneurship and employment through the development of locally adapted herbal formulations. Overall, plant-based preservatives represent a shift toward safer, more profitable, and environmentally responsible postharvest systems, benefiting farmers, consumers, and ecosystems alike.

RIGHT FERTILIZERS AT THE RIGHT TIME: A CROP STAGE-BASED APPROACH FOR HIGHER YIELD AND LOWER COST

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Abstract

An effective nutrient management technique that synchronizes fertilizer delivery with the shifting nutritional requirements of crops at various development stages is crop stage-based fertilization. By providing vital nutrients specifically throughout crucial stages including establishment, vegetative development, blooming, and yield production, this method enhances nutrient usage efficiency in contrast to general fertilizer recommendations. In addition to lowering production costs, improving crop yield and quality, and minimizing environmental contamination, proper timing and split application of fertilizers also minimizes nutrient losses. Its efficacy in a variety of agroclimatic settings is further strengthened by the integration of soil testing, precision instruments, and organic amendments. In general, stage-based fertilization promotes long-term food security, better soil health, and sustainable agriculture.

Keywords: agricultural production, sustainable agriculture, fertilizer usage efficiency, crop stage-based fertilization, and nutrient timing

Introduction

Global agriculture must simultaneously ensure environmental sustainability, conserve limited natural resources, and feed a rapidly expanding population. Although fertilizers are essential for increasing agricultural yield, their ineffective and delayed application frequently results in large nutrient losses, financial waste, and environmental damage. According to estimates, between 30 and 50 percent of applied nutrients are not absorbed by crops worldwide, which causes soil deterioration, runoff, leaching, and volatilization. Conventional fertilizer methods sometimes depend on general guidelines without taking into account the unique nutrient needs of the crop at various stages of growth, which leads to under fertilization during crucial stages and overapplication during times of low need. By delivering nutrients in accordance with the plant's growth stages, crop stage-based fertilization solves these problems and guarantees that nutrients are accessible when the crop most needs them. In addition to increasing crop yield and fertilizer usage efficiency, this strategy also improves soil health, lowers environmental pollution, and supports climate-smart and sustainable farming methods worldwide.

Global Issues with Crop Productivity and Fertilizer Use

Crop yield is still hampered by ineffective nutrient management, despite advancements in agronomy. While precise nutrient management in wealthy countries achieves 50–60% efficiency, fertilizer usage efficiency in underdeveloped parts of Asia, Africa, and Latin America is still low at

30–40%. Financial losses and significant yield discrepancies are the outcomes of inefficient fertilization. While erratic fertilizer distribution and soil degradation hinder availability in semi-arid zones, excessive rainfall in tropical regions speeds up nutrient loss. Soil acidification, greenhouse gas emissions, and water eutrophication are examples of environmental effects. When fertilizer waste and decreased agricultural productivity are taken into account, the worldwide cost of nutrient loss is significant. These difficulties underscore the critical need for effective, globally flexible fertilizer management techniques that maximize output while preserving ecosystems.

Concept and Principles of Crop Stage-Based Fertilization

Aligning fertilizer supply with plant demand is the foundation of crop stage-based fertilization, commonly referred to as growth-stage targeted nutrient management. At every stage of growth, different nutrients are needed.

1. Important nutritional needs by development stage consist of:

- Phosphorus, potassium, and other vital micronutrients to support early vigor and root growth throughout the seedling/establishment stage.
- Vegetative Stage: Nitrogen is necessary for photosynthesis, biomass buildup, and leaf growth.
- blooming/Reproductive Stage: Fruit set, blooming, and successful reproduction depend on balanced nitrogen, potassium, and micronutrients.
- Grain Filling/Maturation Stage: Potassium and certain micronutrients to enhance yield stability, stress resistance, and grain quality.
- Nutrient losses are minimized and absorption is improved by split applications, precise timing, and the use of suitable nutrient sources.
- Global adaptability across different agro-ecologies and cropping systems is made possible by sophisticated monitoring instruments like as leaf color charts, soil sensors, chlorophyll meters, remote sensing, and precision application equipment.

Key Nutrient Requirements for Crop Growth Stages

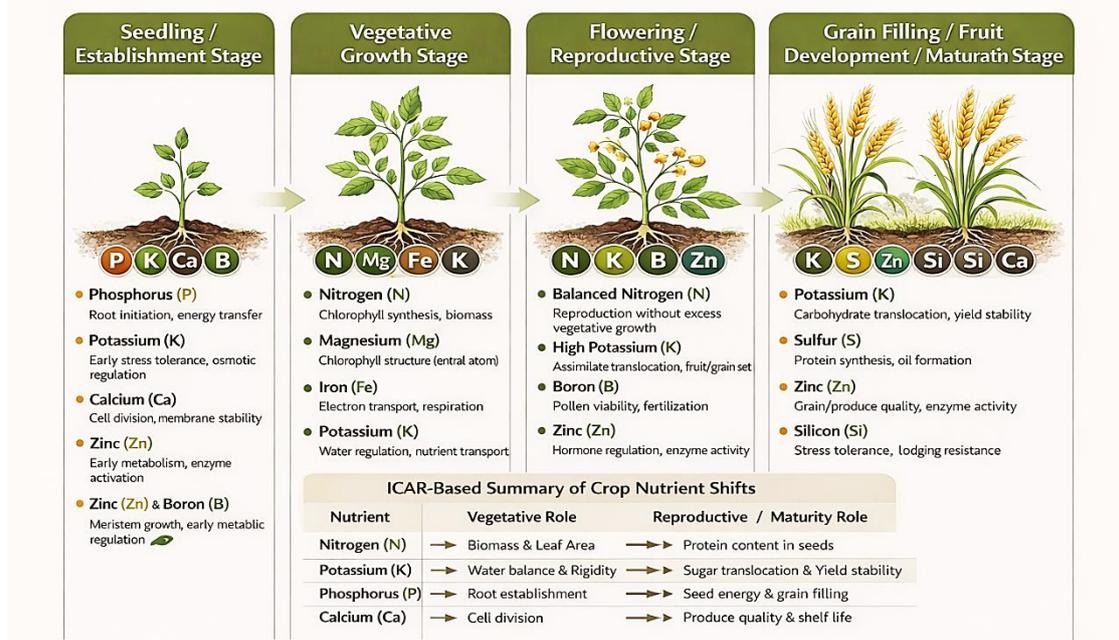


Figure 1. Stage-wise nutrient requirements of crops

Strategies for Global Agriculture Implementation

In order to successfully use stage-based fertilization, local agronomic circumstances, technology, and scientific knowledge must be integrated:

- Soil Testing and Fertility Mapping: A thorough examination of the soil determines the baseline nutrient level and crop-specific requirements.
- Split Application and Nutrient Synchronization: By aligning many dosages with crucial development phases, nutrient absorption is enhanced and loss is reduced.
- Integration of Modern Technology: Nutrient application is optimized via drones, sensors, GIS mapping, variable-rate applicators, and AI-based decision tools.
- Integration with Organic Amendments: Soil structure, water retention, and nutrient cycling are improved when chemical fertilizers are combined with compost, green manure, biofertilizers, and crop residues.
- Agro-Climatic Adaptation: To enhance productivity and yield, fertilization techniques are adapted to temperature, rainfall, soil type, and crop type.

Table 1: Stage-Based Fertilization Schedule

Crop Type	Growth Stage	Nutrient Focus	Application Strategy
Cereals (Wheat, Rice)	Seedling/Vegetative	N, P, K	Basal + split nitrogen
Cereals	Reproductive	K, N	Top-dressing during grain filling
Legumes (Soybean, Chickpea)	Flowering	N, P, Micronutrients	Foliar + soil application
Fruits & Vegetables	Fruit Set/Filling	K, Mg, B	Targeted fertigation/foliar application

Global Benefits and Impacts

There are several agronomic, economic, and environmental advantages to stage-based fertilization.

- Increased Productivity and Nutrient Use Efficiency: Timing nutrients correctly guarantees optimum yield potential and optimal absorption.
- Cost Savings: Lowers production costs, boosts farm profitability, and minimizes fertilizer waste.
- Environmental Protection: Promotes ecosystem health by reducing greenhouse gas emissions, nutrient runoff, and leaching.
- Maintenance of Soil Health: Ensures long-term fertility by preventing nutrient imbalances, soil acidification, and salt accumulation.
- Climate Resilience: Crop resistance to heat, drought, and other environmental stressors is enhanced by a sufficient supply of nutrients throughout crucial phases.
- Sustainable Food Security: Global food security objectives are supported by increased yields, improved crop quality, and effective resource utilization.

Crop-Specific Innovations and Applications

Crop stage-based fertilizing may be customized for various agro-ecological zones and crop types:

- Cereals: Apply potassium at grain filling and split nitrogen during the tillering and reproductive stages.
- Legumes: Nitrogen is either fixed organically or added as needed, while phosphorus and micronutrients are present during blooming.
- Fruits and Vegetables: Fertigation, balanced NPK, and targeted micronutrient treatment throughout blooming and fruiting phases.

- High-Value Crops: Real-time monitoring and nutrient optimization are made possible by integration with precision agricultural equipment, such as drones and Internet of Things sensors.
- Global agricultural systems are becoming more efficient and sustainable because to emerging technologies including biofertilizers, nano-fertilizers, digital agriculture platforms, and AI-driven nutrient management.

Difficulties and Things to Think About

The following are some implementation challenges:

- Knowledge and Training: Farmers need to be educated about crop growth phases, nutrient requirements, and contemporary fertilization procedures.
- Labor and Management: Careful field management and extra labor may be needed for split applications.
- Timeliness and Input Availability: Having access to the right fertilizers at the right times is essential.
- Environmental Factors: Soil types, temperature, and rainfall patterns all have an impact on nutrient availability and may call for modifications.
- Widespread adoption requires addressing these issues through extension services, technological adoption, and legislative assistance.

Prospective Paths and Suggestions

Future advancements in crop stage-based fertilization include:

- Digital Agriculture: AI, smartphone applications, and nutrient management decision-support systems.
- IoT and remote sensing: sensor networks and satellite imaging for accurate nutrient monitoring and application.
- Sustainable Alternatives: Using biofertilizers, slow-release fertilizers, and nanofertilizers more often.
- Policy and Incentive Programs: Promoting precision nutrient management adoption worldwide.
- Integration with Climate-Smart Practices: coordinating crop diversification, conservation agriculture, and water management with nutrient management.

Conclusion

An efficient, scientifically proven method for increasing production, cutting expenses, and preserving soil health is to apply fertilizers at the appropriate crop stage. Higher production, better quality, and long-term sustainability are guaranteed when fertilizer supply and crop demand are synchronized. In order to promote economic viability, environmental stewardship, and global food security, stage-based fertilization combines agronomic research, precision technology, and sustainable practices. Global adoption of this strategy is essential to long-term soil fertility, climate resilience, and sustainable agriculture. (Figure placeholder: Diagram illustrating nutrient demand peaks across crop growth stages for cereals, legumes, and horticultural crops)

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QUALITY ASSESSMENT OF PACKAGED DRINKING WATER: PHYSICO-CHEMICAL, MICROBIOLOGICAL, AND HEAVY METAL PERSPECTIVES

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Abstract

Packaged drinking water has become a major source of potable water in urban and semi-urban regions due to declining confidence in municipal water supplies and increasing demand for convenience. However, evidence from recent studies indicates that packaged water quality varies widely across regions and brands. This review synthesizes findings from national and international studies to evaluate the physico-chemical characteristics, microbiological quality, heavy metal contamination, and overall suitability of packaged drinking water. Studies from India, Nigeria, Kenya, Sri Lanka, Iraq, the United Arab Emirates, and China reveal that while a majority of branded bottled water samples (approximately 70–98%) comply with regulatory standards, a significant proportion of locally packaged and sachet water samples (15–40%) exhibit deviations from permissible limits. Reported concerns include acidic pH values below recommended limits, low total dissolved solids indicating excessive demineralization, and microbial contamination, with heterotrophic plate counts and coliform presence detected in up to 20–30% of samples in certain regions. Trace levels of heavy metals such as lead and cadmium were detected in multiple studies, with occasional exceedances of World Health Organization limits. Water Quality Index assessments classified most branded products as “excellent” or “good,” whereas several locally packaged waters fell into “fair” or “poor” categories. Comparative analyses further indicate that adequately treated municipal water often provides comparable quality at significantly lower economic and environmental costs. The review emphasizes the need for stricter regulatory enforcement, routine post-market surveillance, improved bottling hygiene, and enhanced consumer awareness to ensure long-term public health protection.

Introduction

Safe drinking water is essential for human health and socioeconomic development, yet access to reliably safe water remains a major global challenge. Rapid urbanization, industrialization, population growth, and deterioration of surface and groundwater resources have significantly compromised the quality of municipal water supplies in many regions of the world (Parag & Opher, 2005). As a result, packaged drinking water has emerged as a widely consumed alternative, particularly in urban and semi-urban areas where public confidence in tap water is low (Singla *et al.*, 2014). The global bottled water market has expanded rapidly over the last two decades, driven by consumer perceptions of superior quality, convenience, and safety (More & Chavan, 2025).

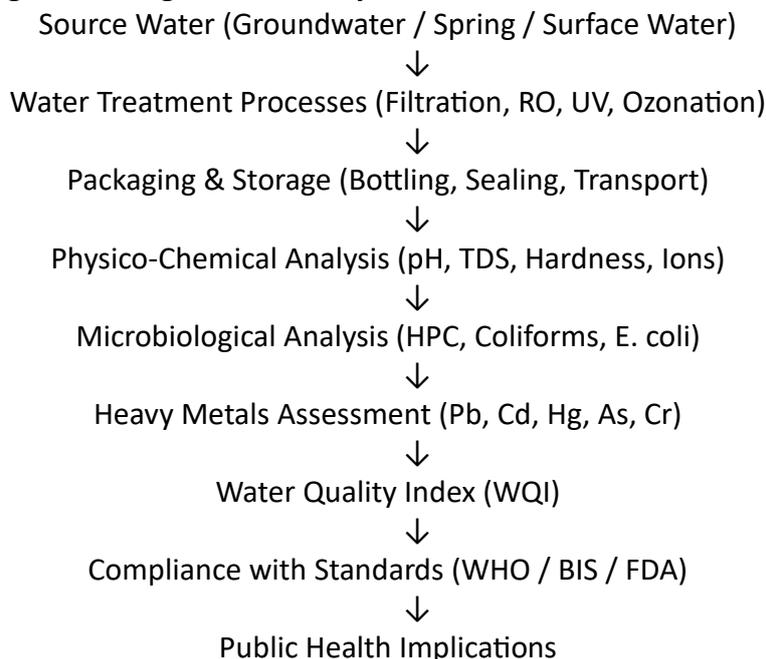
Despite its widespread acceptance, packaged drinking water is not inherently free from quality concerns. Numerous studies have demonstrated that bottled and packaged waters may contain physicochemical imbalances, microbial contaminants, and trace levels of heavy metals that pose potential health risks when consumed over prolonged periods (Sasikaran *et al.*, 2012; Anyanwu & Nwigwe, 2015). In many developing countries, packaged water is regulated as a food product rather

than as drinking water, often resulting in less stringent monitoring and enforcement compared to municipal supplies (Parag & Opher, 2005). As a result, the quality of packaged drinking water shows substantial variation influenced by the source of water, treatment methods, storage practices, and the effectiveness of regulatory monitoring (Sudarsan & Renganathan, 2011).

Physico-chemical parameters such as pH, total dissolved solids, hardness, and mineral composition are critical indicators of drinking water suitability, influencing both palatability and nutritional value (Singla *et al.*, 2014). Similarly, microbiological quality remains a primary public health concern, as the presence of coliform bacteria and heterotrophic microorganisms reflects poor sanitation and increases the risk of waterborne diseases (Okafor-Elenwo & Imade, 2020). In addition, heavy metals such as lead, cadmium, and arsenic have been detected in packaged drinking water in several regions, raising concerns about chronic toxicity and long-term health effects (Ibrahim & Gube-Ibrahim, 2015; Ahmed, 2021).

Given these concerns, systematic evaluation of packaged drinking water using integrated approaches such as Water Quality Index (WQI) and comparative analyses with regulatory standards is essential (Santra & Sarkar, 2023). This review aims to critically synthesize existing research on the physico-chemical, microbiological, and heavy metal quality of packaged drinking water, highlighting key trends, health implications, and the need for improved regulatory surveillance.

Flow Chart of Packaged Drinking Water Quality Assessment



Regulatory Framework and Standards for Packaged Drinking Water

The quality and safety of packaged drinking water are governed by regulatory frameworks that vary significantly across countries, often influencing the degree of compliance and consumer protection. In many regions, packaged drinking water is classified as a food product rather than as potable water, resulting in differences in regulatory oversight, monitoring frequency, and enforcement mechanisms (Parag & Opher, 2005). For instance, in India, packaged drinking water is regulated under the Bureau of Indian Standards (IS 14543), while municipal drinking water is regulated separately under IS 10500, creating disparities in quality surveillance (Singla *et al.*, 2014).

Multiple studies have identified shortcomings in regulatory enforcement, especially in developing nations, where limited inspection capabilities and insufficient post-market surveillance permit substandard products to enter the consumer market (Anyanwu & Nwigwe, 2015; Magut *et al.*, 2024). In Nigeria and Kenya, researchers reported instances of bottled water brands failing to meet microbiological and chemical standards despite regulatory approval, indicating enforcement challenges rather than absence of guidelines (Ibrahim & Gube-Ibrahim, 2015; Magut *et al.*, 2024).

At the global level, the World Health Organization issues guideline values that function as reference points for national regulations; however, compliance with these guidelines remains uneven (Santra & Sarkar, 2023). Studies from the Middle East demonstrate relatively higher compliance rates, though discrepancies between label claims and laboratory findings remain common (Semerjian *et al.*, 2024). These findings emphasize the need for harmonized regulations, routine quality audits, and stronger legal enforcement to ensure the safety of packaged drinking water worldwide.

Physico-Chemical Characteristics of Packaged Drinking Water

Physico-chemical parameters are fundamental indicators of packaged drinking water quality, as they influence taste, stability, and potential health effects. Key parameters commonly assessed include pH, total dissolved solids (TDS), electrical conductivity, hardness, alkalinity, and major ionic constituents such as calcium, magnesium, chloride, and sulfate (Singla *et al.*, 2014). Numerous studies have documented considerable variability in these parameters across brands and geographic regions, primarily attributable to differences in source water characteristics and treatment technologies (Anyanwu & Nwigwe, 2015; Sudarsan & Renganathan, 2011).

pH values of packaged drinking water have frequently been observed to fall below recommended limits, indicating acidic conditions that may lead to corrosion of packaging materials and gastrointestinal discomfort upon prolonged consumption (Sasikaran *et al.*, 2012). Low TDS levels, often promoted as a marker of purity, may instead reflect excessive demineralization during treatment processes such as reverse osmosis, resulting in reduced concentrations of essential minerals like calcium and magnesium (Semerjian *et al.*, 2024). This loss of mineral content has been linked to potential nutritional deficiencies and altered electrolyte balance (More & Chavan, 2025).

Comparative studies have also demonstrated that municipal drinking water often exhibits higher mineral stability compared to packaged water, challenging the perception that bottled water is nutritionally superior (Singla *et al.*, 2014). These findings underscore the importance of monitoring physico-chemical properties to ensure that packaged drinking water is not only microbiologically safe but also chemically balanced and suitable for long-term consumption.

Microbiological Quality of Packaged Drinking Water

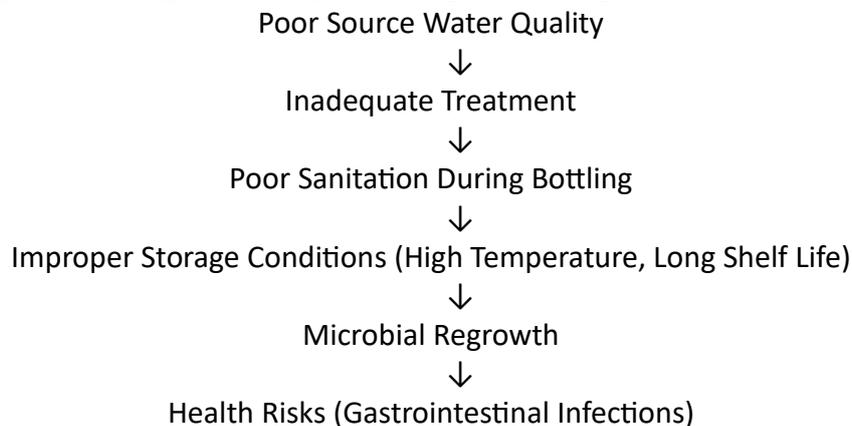
Microbiological safety is a critical determinant of drinking water quality, as the presence of pathogenic and indicator microorganisms poses immediate public health risks. Although packaged drinking water is often perceived as sterile, several studies have reported microbial contamination in bottled and sachet water samples, indicating lapses in treatment, packaging, or storage conditions (Okafor-Elenwo & Imade, 2020; Magut *et al.*, 2024). Commonly assessed microbiological indicators include heterotrophic plate count (HPC), total coliforms, fecal coliforms, and *Escherichia coli*, which serve as markers of sanitary quality and potential fecal contamination (Sasikaran *et al.*, 2012).

Research conducted in India, Sri Lanka, Nigeria, and Kenya has revealed detectable levels of HPC bacteria in several packaged water brands, with some samples exceeding recommended limits

despite regulatory approval (Singla *et al.*, 2014; Sasikaran *et al.*, 2012). Although heterotrophic bacteria are not necessarily pathogenic, elevated counts indicate inadequate hygiene practices and may facilitate the survival of opportunistic pathogens under favorable conditions (Thoidingjam *et al.*, 2020). In some cases, the presence of coliform bacteria and fungal contaminants has been linked to post-treatment contamination during bottling or prolonged storage at ambient temperatures (Sudarsan & Renganathan, 2011).

Storage duration, exposure to heat, and absence of residual disinfectants have been identified as major factors promoting microbial regrowth in packaged drinking water (Parag & Opher, 2005). These findings emphasize the necessity of stringent microbiological monitoring, improved sanitation during production, and proper storage practices to minimize health risks associated with packaged drinking water consumption.

Factors Affecting Microbiological Quality of Packaged Drinking Water



Heavy Metal Contamination in Packaged Drinking Water

Heavy metal contamination in packaged drinking water has emerged as a significant public health concern due to the toxic and bioaccumulative nature of these elements. Metals such as lead (Pb), cadmium (Cd), mercury (Hg), arsenic (As), chromium (Cr), and iron (Fe) can enter bottled water through contaminated groundwater sources, inadequate treatment processes, or leaching from pipes and packaging materials (Ibrahim & Gube-Ibrahim, 2015; Ahmed, 2021). Even at trace concentrations, prolonged exposure to heavy metals can result in serious health effects, including neurological disorders, renal damage, and increased cancer risk (Cohen *et al.*, 2022).

Studies conducted in Nigeria and Kurdistan have reported detectable levels of heavy metals in packaged drinking water, with some samples exceeding World Health Organization permissible limits, particularly for cadmium and lead (Ibrahim & Gube-Ibrahim, 2015; Ahmed, 2021). Although several investigations found metal concentrations within acceptable standards, the cumulative effects of daily consumption remain a concern, especially in populations relying exclusively on packaged water as their primary drinking source (Santra & Sarkar, 2023). Variations in heavy metal concentrations among brands further suggest inconsistencies in source water quality and treatment efficiency (Semerjian *et al.*, 2024).

The presence of heavy metals underscores the importance of regular monitoring and advanced treatment methods such as activated carbon filtration and ion exchange to ensure consumer safety (Ahmed, 2021). Strengthening regulatory oversight and enforcing stringent quality control measures are essential to minimize chronic exposure risks associated with packaged drinking water.

Water Quality Index (WQI) and Overall Assessment of Packaged Drinking Water

The Water Quality Index (WQI) is a widely used tool for integrating multiple physico-chemical and microbiological parameters into a single numerical value that represents the overall suitability of water for drinking purposes. WQI simplifies complex datasets and enables effective communication of water quality status to policymakers, researchers, and consumers (Santra & Sarkar, 2023). Several studies have applied WQI to assess packaged drinking water quality and categorize samples into classes such as excellent, good, fair, or poor based on compliance with established standards (Anyanwu & Nwigwe, 2015).

Studies from India and Nigeria revealed that although the majority of branded bottled water samples were classified within the “excellent” to “good” WQI categories, locally produced and sachet waters often fell into the “fair” or “poor” categories, mainly due to variations in pH, nitrate concentration, microbial load, and total dissolved solids. (Sudarsan & Renganathan, 2011; Anyanwu & Nwigwe, 2015). In a comparative study, Santra and Sarkar (2023) reported that 98% of branded bottled water samples met excellent quality standards, whereas a significant proportion of locally packaged water failed to achieve acceptable WQI scores.

The application of WQI also highlights inconsistencies between regulatory compliance and actual water quality, as some samples with certification still exhibited unfavourable index values (Singla *et al.*, 2014). These findings reinforce the utility of WQI as a comprehensive assessment tool and emphasize the need for its routine application in packaged drinking water monitoring programs to ensure consistent quality and public health protection.

Comparative Analysis of Packaged and Municipal Drinking Water

Comparative studies between packaged drinking water and municipal water supplies have provided important insights into their relative safety, nutritional value, and overall quality. While packaged water is widely perceived as safer, several investigations indicate that municipal drinking water often demonstrates comparable or superior physico-chemical stability when adequately treated and monitored (More & Chavan, 2025; Singla *et al.*, 2014). Municipal water typically contains balanced mineral concentrations due to controlled treatment processes, whereas packaged water may undergo excessive purification, resulting in reduced essential mineral content (Semerjian *et al.*, 2024).

Microbiological assessments have shown mixed results. In some cases, packaged water exhibited lower microbial counts than municipal water, supporting consumer preferences; however, other studies reported post-treatment contamination in bottled water due to poor hygiene during bottling or improper storage conditions (Okafor-Elenwo & Imade, 2020; Magut *et al.*, 2024). While municipal water may be exposed to contamination during distribution, residual disinfectants inhibit microbial regrowth, a safeguard typically absent in packaged water. (Parag & Opher, 2005).

Chemical contamination, particularly from heavy metals, has been reported in both water sources, though packaged water contamination is often linked to groundwater sources and packaging materials (Ahmed, 2021; Ibrahim & Gube-Ibrahim, 2015). These findings challenge the assumption that packaged drinking water is inherently superior and highlight the importance of strengthening public water infrastructure while ensuring stringent quality control across both water supply systems.

Health Implications of Long-Term Consumption of Packaged Drinking Water

Long-term consumption of packaged drinking water has important health implications that depend on its chemical composition, microbiological safety, and contaminant levels. Despite regulatory

compliance among many packaged water brands, sustained consumption of demineralized water may result in insufficient levels of calcium and magnesium, thereby affecting bone health, cardiovascular function, and metabolic processes (More & Chavan, 2025; Semerjian *et al.*, 2024). Studies have suggested that demineralized water produced through reverse osmosis may disrupt electrolyte balance when consumed exclusively over extended periods (Singla *et al.*, 2014).

Microbiological contamination, even at low levels, presents additional risks, particularly for immunocompromised individuals, children, and the elderly. Elevated heterotrophic bacterial counts and the presence of opportunistic pathogens have been linked to gastrointestinal disorders and heightened vulnerability to infections, particularly when hygienic practices during bottling and storage are insufficient (Okafor-Elenwo & Imade, 2020; Thoidingjam *et al.*, 2020). Furthermore, chronic exposure to trace amounts of heavy metals such as lead and cadmium through packaged drinking water may result in cumulative toxicity, affecting neurological, renal, and developmental health over time (Ibrahim & Gube-Ibrahim, 2015; Ahmed, 2021).

These findings underscore the importance of not only meeting short-term safety standards but also ensuring the long-term nutritional and toxicological suitability of packaged drinking water through continuous monitoring and improved quality control measures (Santra & Sarkar, 2023).

Environmental and Economic Impacts of Packaged Drinking Water

The rapid expansion of the packaged drinking water industry has raised significant environmental and economic concerns alongside quality and health issues. One of the most critical environmental impacts is plastic waste generation, as bottled water packaging contributes substantially to global plastic pollution. Single-use polyethylene terephthalate (PET) bottles frequently accumulate in landfills or enter aquatic ecosystems as a result of insufficient recycling infrastructure, particularly in developing regions (Parag & Opher, 2005; Cohen *et al.*, 2022). The production, transportation, and disposal of bottled water also result in higher carbon emissions compared to municipal water supplies, exacerbating environmental sustainability challenges (Gleick & Cooley, 2009).

From an economic perspective, packaged drinking water is significantly more expensive than municipal water, often costing hundreds of times more per litre. Despite this, consumers continue to rely on packaged water due to concerns about tap water safety and inconsistent public supply systems (More & Chavan, 2025). Studies indicate that low-income populations may spend a disproportionate share of their income on packaged water, creating issues of social equity and access to safe drinking water (Santra & Sarkar, 2023). Moreover, the growing commercial focus on bottled water may divert attention and investment away from improving public water infrastructure (Parag & Opher, 2005).

These environmental and economic implications highlight the need for balanced policies that promote safe municipal water systems, responsible packaging practices, and sustainable consumption of packaged drinking water.

Conclusion

This review highlights that packaged drinking water, despite its widespread perception as a safe alternative to municipal supplies, exhibits considerable variability in quality across regions and brands. Evidence from multiple studies indicates that physico-chemical imbalances such as low pH and reduced mineral content, along with microbiological contamination and trace levels of heavy metals, remain persistent concerns (Singla *et al.*, 2014; Sasikaran *et al.*, 2012; Ahmed, 2021). The

occurrence of these issues suggests gaps in treatment efficiency, storage practices, and regulatory enforcement. Water Quality Index assessments further reveal that regulatory approval does not always guarantee optimal water quality, particularly for locally packaged products (Santra & Sarkar, 2023). Comparative findings show that adequately treated municipal water can provide comparable or superior quality at lower economic and environmental costs (More & Chavan, 2025). Therefore, strengthening regulatory surveillance, improving production hygiene, ensuring accurate labelling, and promoting sustainable water management are essential to protect public health and ensure safe drinking water access.

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ROLE OF BANANA TISSUE CULTURE IN TRANSFORMING INDIAN AGRICULTURE

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Tissue culture, a technique of growing a plant part in a glass bottle (*in vitro*) under aseptic (free from microorganisms) and controlled conditions, is a vital development in agriculture. This technique offers advantages such as rapid mass multiplication, improving crop production (including haploid production, wide hybrids, and wide crossing), the production of disease-free planting materials, and the conservation of genetic resources. Tissue culture has contributed significantly to boosting agricultural production by providing high-quality planting material. Furthermore, it has also helped to address crop-specific problems, such as the production of female plants, virus elimination, shortening breeding cycle, hybrid fixation and improved germination.

Banana is one of the most widely consumed and economically important fruits globally. It is a powerhouse of essential nutrients providing a significant source of potassium, vitamin B6, and vitamin C. Bananas are cultivated on approximately 0.85 million hectares with an annual output exceeding 30 million metric tons. Unlike many other fruits, cultivated bananas are sterile and do not produce viable seeds making vegetative propagation a viable and crucial method. Conventionally, banana is propagated with suckers, which are vegetative offshoots that emerge from the underground stem known as the rhizome or corm of the parent plant. This method leads to season-dependent availability of limited planting material as well as heterogeneity in planting material resulting in reduced yields and income for farmers.

Tissue culture has revolutionized banana cultivation by offering large-scale, rapid multiplication of bananas. This also ensured the availability of genetically uniform, high-performing, disease-free planting material and vigorously growing plantlets. Micropropagation of banana offers numerous benefits including rapid multiplication of plantlets with a limited requirement of mother stock material, higher field establishment rate, uniform growth, synchronized harvesting, early maturity, superior fruit quality and increased production. This technique ensures high product uniformity among the resulting plants and allows for season-independent production making it highly reliable. Furthermore, the practice provides significant agronomic advantages and is crucial for the production of disease-free planting material, ultimately leading to high returns for the growers.

Overview of Banana Micropropagation

Micropropagation of banana is a systematic, multi-step process for producing large quantities of genetically identical and disease-free planting material. It begins with the meticulous selection and establishment of a disease-free mother block nursery, where superior mother plants undergo rigorous virus indexing to ensure purity. Explants, typically shoot tips isolated from sword suckers, are surface-sterilized before being placed in a culture initiation medium. The explant is then transferred to a multiplication medium for culture proliferation, where axillary buds are induced to form clusters of proliferating shoots. This is repeated over several subculture cycles to achieve rapid multiplication. Finally, the resulting plantlets are transferred to a rooting medium and then undergo

primary and secondary hardening (acclimatization) in a controlled environment before being moved to the field. This technique is crucial for mass-producing uniform and healthy banana plants.

Critical Problems in Banana Tissue Culture:

1. **Necrosis:** Non-pathogenic dieback of shoot tips; tips turn brown and may die, often due to nutrient imbalance and poor culture conditions.
2. **Stem abnormalities:** Abnormal flattening/widening of the stem caused by failure of lateral branches to separate from the main stem during growth.
3. **Somaclonal variation:** Epigenetic changes involve temporary, reversible changes in gene expression (e.g., DNA methylation). Soma-clonal variation involves genetic changes that may be permanent and heritable.
4. **Tissue browning:** Excess phenolics in explant cause browning and reduced growth.



Sword Sucker



Tissue Culture Process



Ex-plant Initiation



Proliferation



Hardened Plantlets



Hardening Process



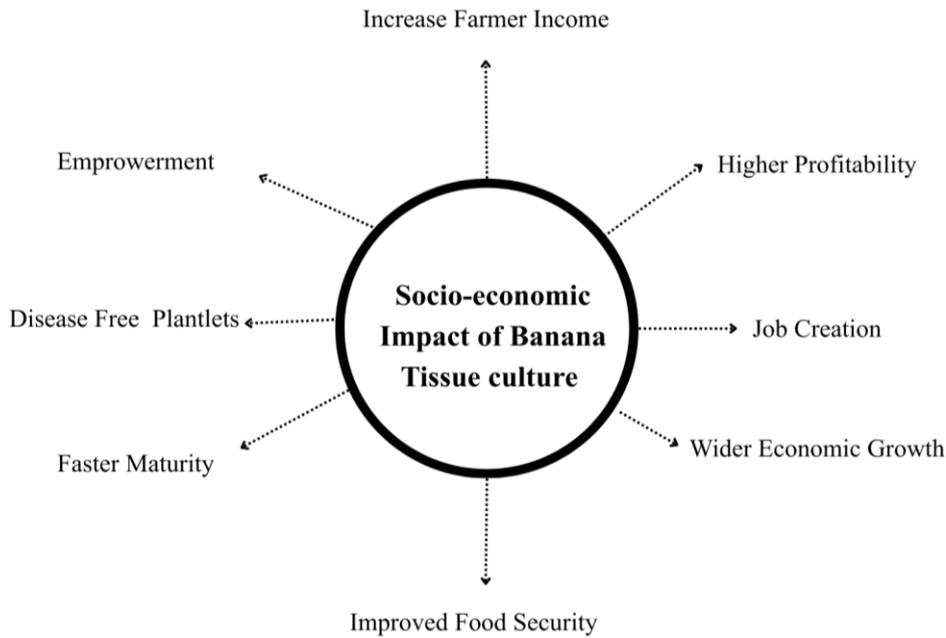
Rooted Plantlet

Overview of Banana Plant Tissue Process

Socio-Economic impacts

- **Increase Farmer Income:** Adoption of tissue culture (TC) banana can significantly increase farm income and overall household earning due to higher yield and better fruit quality.
- **Higher Profitability:** TC banana cultivation gives higher net returns per hectare with a favourable benefit–cost ratio compared to sucker-grown bananas.
- **Job Creation:** TC banana farming creates more job opportunities, especially for women and youth in nursery, cultivation and marketing activities.
- **Wider Economic Growth:** The higher productivity and profitability increase the living standards of rural people.
- **Improved Food Security:** TC banana growers experience reduced food insecurity and better access to food due to stable income.
- **Disease-Free Plantlets:** TC plants are healthy and disease-free, resulting in lower crop loss and consistent production.

- **Faster Maturity:** TC banana plants grow faster and mature early, allowing quicker harvesting and faster returns.
- **Empowerment:** The technology strengthens small farmers economically and promotes positive social change.



Socio-economic impact of banana tissue culture

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SELECTING QUALITY PLANTING MATERIAL: BUILDING THRIVING FRUIT ORCHARDS IN HIMACHAL PRADESH

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In the pleasant hills of Himachal Pradesh, where apple, pear, peach, persimmon, kiwi and stone fruit orchards dot the landscape, fruit cultivation is more than a livelihood, it's a legacy passed down through generations. From the temperate valleys of Shimla and Solan to the high-altitude regions of Kinnaur and Lahaul-Spiti, these orchards drive rural economies and contribute to India's horticultural exports. Yet, the foundation of every successful orchard lies in one often-overlooked element: the quality of planting material. Substandard saplings can lead to uneven growth, disease outbreaks, delayed fruiting, and significant financial losses, turning years of hard work into disappointment.



Figure 2. Farmers holding apple and other nursery plants in Kinnaur

As emphasized by experts at Dr Y.S. Parmar University of Horticulture and Forestry (YSPUHF) in Nauni, Solan, India's leading horticulture institution, investing in high-quality, certified plants is essential for long-term productivity. In response to farmers' complaints about inconsistent plant quality and uniform pricing for varying standards, YSPUHF formed a committee in 2023. Their

recommendations, adopted in 2024 and continuing into 2025, introduced a transparent grading system (Grades A, B, and C) based on measurable criteria like root count, height, stem thickness, and health. This system ensures farmers get value for their money: premium prices for top-grade plants with superior vigour, and affordable options for lower grades that still meet basic disease-free and true-to-type standards.

Why Quality Matters for Himachal Farmers

Himachal's challenging terrain, with its steep slopes, variable rainfall, and risk of frost, demands resilient planting material. High-quality saplings offer:

- **Higher Survival and Uniform Growth:** Vigorous roots and balanced tops ensure quick establishment, reducing field mortality and leading to even canopies for synchronized fruiting from the third or fourth year.
- **Superior Yields and Fruit Quality:** Certified plants produce larger, blemish-free fruits with better taste, fetching premium market prices in domestic and export markets.
- **Disease Resistance:** They minimize the spread of pathogens, protecting orchards that can remain productive for greater than 45 years.
- **Economic Security:** Avoiding cheap, ungraded stock from unreliable sources prevents losses that could run into lakhs per hectare, especially in high-density plantations common in Himachal.

In contrast, substandard plants often carry hidden infections, weak roots, or off-type varieties, resulting in patchy orchards and low returns.



Figure 2. A Grade Apple plants



Figure 3. B Grade Apple plants



Figure 4. C Grade Apple plants

Key Criteria for Selecting Fruit Plants

Himachal farmers should always source plants from registered nurseries accredited by the Himachal Pradesh Horticulture Department, YSPUHF, or the National Horticulture Board (NHB). Look for proper labels detailing variety, rootstock, age, grade, and certification. Key selection points include:

1. Plant Type and Age:

- One-year-old whip plants (straight, unbranched grafts) for pome and stone fruits like apple, pear, peach, plum, and cherry, deal for shaping and cost-effective for large-scale planting.
- Two-year-old feathered plants (with lateral branches) for faster canopy development and earlier bearing.

2. Graft Union and Stem:

- A healthy, fully healed union without swelling, decay, or cracks, positioned 10-30 cm above the root collar.
- Straight central leader (main stem), at least pencil-thick, free from injuries or bark damage.

3. Root System:

- Well-developed, fibrous roots with a strong taproot for anchorage and drought tolerance.
- Avoid damaged, twisted, dry, or deficient feeder roots.

4. Overall Health:

- No signs of pests, diseases, nutrient deficiencies, or dehydration, plants should be turgid and vigorous.

Common Diseases to Avoid

Inspect plants thoroughly and reject any showing these red flags, as they can devastate entire orchards:

- **Crown Gall (*Agrobacterium tumefaciens*):** Tumour like swellings at the crown, roots, or graft union that crack and decay, weakening plants and inviting secondary infections.
- **Hairy Root (*Agrobacterium rhizogenes*):** Clusters of thin, hair-like roots from a single point, disrupting hormone balance and growth.
- **Root Rot:** Browning, softening, or foul-smelling roots indicating fungal issues.
- **Woolly Apher Galls:** White, cottony secretions with spongy knots on roots or stems.



Figure 5. Hairy root problem in nursery plants of apple

YSPUHF Grading Standards: Your Guide to Quality

YSPUHF's grading system can now may use as standard across Himachal's accredited nurseries, categorizes plants as disease-free and true-to-type while allowing price differentiation based on vigour. Here's a summary:

For whip plants (1-year-old, unfathered)

Parameter	Grade A	Grade B	Grade C
Number of Roots	>4	3-4	<3
Whip Appearance	Straight, >60 cm	Straight, 40-60 cm	Straight, <40 cm
Plant Height (cm)	>120	70-120	<70
Disease/Pest Symptoms	None visible	None visible	None visible
Calliper (mm) above 10 cm of graft union	>12	9-12	<9



Figure 6. A Grade Apple plants



Figure 7. B Grade Apple plants



Figure 8. Farmer with various grade Apple plants

For Feathered Plants (2-Year-Old)

Parameter	Grade A	Grade B	Grade C
Number of Roots	>6	3-6	<3
Central Leader Appearance	Straight	Slightly bent	Crooked/Misshapen
Disease/Pest Symptoms	None visible	None visible	None visible
Number of Lateral Shoots	>6	4-6	<4
Calliper (mm) above 10 cm of graft union	12-15	9-12	<9

Grade A plants are best for high-value, intensive farming, while Grade C offers budget-friendly options without compromising basics.

Practical Tips for Himachal Farmers

To maximize your orchard's potential, follow these YSPUHF-recommended steps:

- Source Wisely:** Buy from YSPUHF nurseries or state-registered outlets. Consult local horticulture officers for verified lists, avoid roadside sellers.
- Verify Documentation:** Demand labels and certifications confirming scion from certified mother blocks.
- Inspect Thoroughly:** Measure calliper, count roots, and check for diseases. Choose grades based on your budget and needs—Grade A for premium performance.
- Handle with Care:** Keep roots moist during transport (use wet gunny sacks or mud slurry). If delayed, heel-in plants in shaded soil.
- Pre-Planting Protection:** Dip roots in biocontrol agents like *Trichoderma*, *Pseudomonas*, or *Agrobacterium*, especially in gall-prone areas.
- Document Everything:** Retain invoices and photos for disputes or references.

By embracing these standards, Himachal farmers can build resilient orchards that thrive amid climate challenges, boost yields, and secure sustainable incomes. As the state pushes for horticultural excellence, quality planting material isn't just a choice, it's the smart investment for a fruitful future. For more guidance, reach out to YSPUHF extension services or your district horticulture office.

STUDY OF DEEP EUTECTIC SOLVENTS AND THEIR APPLICATIONS IN FOOD PROCESSING

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Abstract

Deep Eutectic Solvents, or simply DES, are regarded as an upcoming category of eco-friendly solvents that are generated through the fusion of two or more substances, HBD, and HBA, which are the mainstay in the formation of a eutectic mixture due to their strong hydrogen intermolecular forces. The resultant melt is of a much lower temperature than that of the starting materials. DES are said to be non-volatile, non-combustible, have adjustable chemical and physical attributes, are bio-friendly, and require simple procedures for preparation, hence, their gradual transition to use as conventional solvents and ionic liquids replacement has continued more than the last decades. They have opened up areas of application in medical and pharmaceutical industries, especially in the extraction and processing of bioactive compounds, proteins, lipids, pigments, and other food ingredients that have high value or are considered waste. The present article is a comprehensive review of the mechanisms, classifications, preparations, properties, and uses of DES with the specific focus on food and processing engineering.

Keywords: Deep eutectic solvents, food processing, green solvents, bioactive extraction, natural DES

Introduction

The application of solvents is a predominantly accepted practice in the food and processing industries, which they utilize to acquire, separate, purify, and blend the desired components like oils, proteins, pigments, flavours, and nutraceuticals. The main solvents used during these operations are often hexane, methanol, acetone, and chloroform because of their high efficiency. In addition, these solvents have been the primary environmental and health concern due to their toxicity, volatility, and flammability. Hence, the increasing restrictions imposed by regulations and the consumers' demand for sustainable and clean-label food products have pressed for the search of eco-friendly alternatives more than ever. In this regard, Deep Eutectic Solvents (DES) have been pointed out as green solvents that are in complete harmony with the principles of green chemistry and sustainable food processing (Abbott et al., 2003; Smith et al., 2014).

How Deep Eutectic Solvent Formed and Work

A eutectic mixture is a term that describes a mixture of two or more substances in a single phase that has a melting point lower than the melting points of all the components. In deep eutectic solvents, the melting point lowering is due to very strong hydrogen bonding between the hydrogen bond donor and hydrogen bond acceptor. The compound's melting points are lowered as a result of these interactions since they prevent the atoms in the solid from being in the fixed positions of the regular lattice and thus lead to charge being more spread out and lattice energy being reduced. Quaternary ammonium salts are usually the hydrogen bond acceptors, which include choline chloride, while urea, glycerol, organic acids, sugars, or amino acids are the hydrogen bond donors.

One classic case is the choline chloride–urea mixture that turns liquid at about 12 °C, although the individual substances have high melting points. This property is what makes DES applicable in low-temperature food processing (Abbott et al., 2003).

Different Types of Deep Eutectic Solvents

Based on their chemical composition, deep eutectic solvents are divided into four large categories. The first class of deep eutectic solvents (Type I) is characterized by the presence of a quaternary ammonium salt along with a metal chloride, whereas the second class (Type II) is characterized by a quaternary ammonium salt and a hydrated metal chloride. The two types are primarily utilized in electrochemical and metallurgical applications and not in food processing. The third category of DES is the most important one from the standpoint of food and processing engineering since it consists of a quaternary ammonium salt and an organic hydrogen bond donor such as glycerol, lactic acid, citric acid, sugars, or polyols. These types are very low in toxicity, biodegradable and possess outstanding solvating power (Paiva et al., 2014). The last class of deep eutectic solvents (Type IV) combines metal salts with hydrogen bond donors and finds applications mostly in chemical synthesis.

Natural Deep Eutectic Solvents (NADES)

Natural Deep Eutectic Solvents (NADES) are considered a DES subclass entirely formed of natural metabolites like sugars, organic acids, amino acids, choline derivatives, and water. Because of their biocompatibility, low toxicity, and possible food-grade status, NADES become very appealing for food and bioprocessing applications. The solvents are purported to exist in living cells naturally and may help in the dissolution and stabilization of biomolecules. Among the NADES are choline chloride–citric acid, glucose–fructose–water, and proline–malic acid systems that have demonstrated their capability of extracting nutraceutical and functional food compounds at high efficiency (Dai et al., 2013; Liu et al., 2018).

Preparation of Deep Eutectic Solvents

The preparation of deep eutectic solvents is a very straightforward, cost-effective, and eco-friendly process. The most frequent approach is to mix the donor and the acceptor of hydrogen bonds in defined proportions and heat them very lightly, between 50 and 80 °C, with stirring all the time, until a liquid that is clear and homogenous is formed. This procedure is free from chemical reactions, catalysts, and wastes of solvents, which is the reason why it can be called sustainable processing (Zhang et al., 2012). Sometimes, the components of DES can also be ground together at room temperature, which not only leads to the production of the DES but also consumes less energy in the process.

Physicochemical Properties of Des

The physicochemical properties of Deep Eutectic Solvents (DES) are the main factors that affect their suitability in food and processing applications. DESs are often characterized by low melting points which allow for the processing of the product at milder thermal conditions that are less damaging to the heat-sensitive nutrients. They have a higher viscosity compared to traditional solvents which although may limit the ease of transfer of the substances could be compensated for by either temperature increase or controlled water addition. The density of DESs is usually around 1.0 - 1.3 g/cm³ which is coupled with a high polarity that makes them capable of dissolving a variety of polar and semi-polar food components like sugars, proteins, polyphenols, and organic acids. The majority of DESs are characterized by high-temperature thermal stability of up to 200–300 °C thus making them applicable for a wide range of food processing operations (Smith et al., 2014).

Applications of Des in Food and Processing Engineering

In the extraction of bioactive compounds, the like of polyphenols, flavonoids, anthocyanin, carotenoids and antioxidants from fruits, vegetables, herbs and agro-industrial residues deep eutectic solvents have been very widely applied. The use of DES in comparison to the use of traditional solvents has often resulted in greater yields of the extracts and better retention of biological activity (Ruesgas-Ramón et al., 2017; Cunha et al., 2018). In addition, DES are to separate and purify proteins from plants like legumes, oilseed cakes and cereal by products while keeping their functional properties. In the case of lipid processing, the usage of DES has been studied as a green solution for oil extraction and as a degumming agent and for free fatty acids removal, thus replacing hexane. Moreover, they have been able to successfully extract the natural pigments and flavour compounds, which is a great support for the clean-label food production (Cunha et al., 2018). Furthermore, the use of DES can be seen as a positive factor for the enzymes since it can increase their stability and activity, which is very helpful in processes such as bio-catalysis, fermentation, and enzymatic hydrolysis.

Use of Des in Biomass Pretreatment and Waste Utilization

In the field of agricultural and processing engineering, the application of Deep Eutectic Solvents (DES) for the pre-treatment of lignocellulose biomass, where lignin is removed and enzymatic hydrolysis is enhanced, is gaining acceptance. This practice aids the transformation of agricultural wastes into biofuels, biochemical sources, and food ingredients with increased value, thereby facilitating the adoption of strategies such as circular bio-economy and waste valorisation (Xu et al., 2016).

Advantages of Deep Eutectic Solvents

Deep eutectic solvents are very promising due to their numerous benefits viz. being eco-friendly, biodegradable, having low vapour pressure, not being flammable, being easily prepared, having high extraction efficiency and being compatible with food-grade components. Thus, these solvents can be considered as a good choice for traditional solvents replacement in the food processing industries.

Limitations and Challenges

There are several advantages when it comes to DES however, they come along with challenges such as high viscosity, moisture absorption, lack of sufficiently large toxicological and regulatory data for some systems, and the difficulties of solvent recovery and reuse. To overcome the obstacles posed by these challenges it must be done on an industrial scale and thus large-scale industrial adoption is essential.

Future Scope

It is expected that the next researches on the subject of DES in food engineering and processing will focus on the production of NADES with low viscosity and food compatibility, improved safety and toxicological evaluations, coupling with modern extraction methods such as ultrasound and microwave assisted processing, and large-scale industrial trials.

Conclusion

Deep Eutectic Solvents are a very adaptable and eco-friendly group of solvents that have already started to show their huge potential in the area of food and processing engineering. Their adjustable characteristics, easy preparation, and compatibility with natural and food-grade materials are the major reasons why they are considered to be the best eco-friendly solvent alternatives to traditional

organic solvents. Their extraction of bioactive compounds, proteins, lipids, pigments, enzyme stabilization, and biomass pre-treatment are some of the applications that underscore their significance in the sustainability of food processing. In spite of this, the issues of high viscosity, hygroscopic nature, and lack of extensive regulatory data still exist, but it is believed that further research and validation in the industry would help to remove these barriers. Thus, DES and especially Natural Deep Eutectic Solvents will definitely be a major factor in the promotion of eco-friendly and efficient food and processing technologies in the future.

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GUT–BRAIN AXIS IN FARM ANIMALS: WHY STRESS CAN STOP THE RUMEN BEFORE THE FEED ENDS

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Abstract

Farm animals are frequently observed refusing feed even when sufficient fodder is available, a behavior often attributed by farmers to temperament or feed quality. Contemporary research, however, identifies disruption of the gut–brain axis as a key underlying cause. This bidirectional communication system linking the central nervous system with rumen physiology and microbial populations is highly sensitive to stress. Stressors such as heat exposure, rough handling, transport, and overcrowding elevate cortisol and catecholamines, suppress vagal activity, impair rumen motility, and disturb microbial fermentation. These changes lead to reduced appetite, altered cud chewing behavior, and production losses, particularly in milk yield. Smallholder dairy systems in India are especially vulnerable due to climatic extremes and management-related stress. This review outlines the physiological mechanisms by which stress inhibits rumen function and highlights low-cost, farmer-friendly interventions—such as gentle handling, shade provision, electrolyte supplementation, and gradual dietary transitions—that can restore intake and productivity. Strengthening the gut–brain–rumen connection offers a practical pathway to improved animal welfare and enhanced farm profitability.

Keywords: Gut–brain axis, rumen function, stress physiology, cortisol, feed intake, dairy management

Introduction

Across Indian dairy systems, farmers commonly report that animals stop eating despite the presence of adequate green and dry fodder. Expressions such as “*charra hai par kha nahi rahi*” are frequently heard in rural and peri-urban sheds. While such cases are often blamed on feed spoilage or animal behavior, advances in veterinary physiology suggest a more complex explanation rooted in neurogastrointestinal regulation.

The gut–brain axis refers to the continuous two-way communication between the nervous system and the gastrointestinal tract. In ruminants, this interaction is particularly critical because rumen motility, microbial fermentation, and feed intake are tightly regulated by neural and hormonal signals. Stress can rapidly disrupt this balance, resulting in reduced rumination, impaired digestion, and a decline in production. Understanding this relationship is essential for addressing unexplained off-feed conditions in dairy animals.

Pathways of Gut–Brain Communication

The rumen and brain communicate through integrated neural, endocrine, and microbial pathways:

1. Neural Signaling via the Vagus Nerve

The vagus nerve serves as the primary conduit for sensory information from the rumen to the brain. Reduced vagal tone during stress slows rumen contractions and suppresses cud chewing, directly affecting digestion efficiency.

2. Endocrine and Hormonal Pathways

Activation of the hypothalamic–pituitary–adrenal (HPA) axis during stress increases cortisol and adrenaline secretion. These hormones redirect blood flow away from the digestive system, suppress hunger signals, and interfere with rumen fermentation.

3. Microbial–Neurochemical Interactions

Rumen microorganisms produce metabolites such as volatile fatty acids and neuroactive compounds that influence brain signaling. Stress-induced microbial imbalance (dysbiosis) disrupts these signals, further impairing appetite regulation and rumen stability.

Under normal conditions, these pathways maintain optimal rumen pH (approximately 6.2–6.8), efficient fermentation, and consistent feed intake. Stress can destabilize this system within a short period.

Impact of Stress on Rumen Physiology

Several stressors commonly encountered on Indian farms exert measurable effects on rumen activity:

Heat Stress : Exposure to temperatures exceeding 35 °C increases respiration rate and circulating cortisol levels, leading to reduced rumen contractions and lower volatile fatty acid production.

Handling and Transport Stress : Rough handling, shouting, and prolonged transport disrupt neural signaling through the vagus nerve, often resulting in reduced feed intake for up to two days after the event.

Social and Housing Stress : Overcrowding and inadequate space allowance cause sustained cortisol elevation, shortening daily rumination time and impairing digestive efficiency. Collectively, these stressors compromise feed utilization and contribute to declines in milk yield and overall productivity.

Observable Field Indicators of Gut–Brain Disruption

Farmers and veterinarians can identify early signs of stress-related rumen dysfunction through simple observations:

- Reduced cud chewing duration (less than 4 hours per day)
- Inconsistent manure consistency, ranging from watery to overly firm
- Increased ear flicking and tail movement during rest
- Reluctance to approach the feed trough and altered posture

Monitoring these indicators allows early intervention before significant production losses occur.

Practical Management Interventions:

Immediate, Low-Cost Stress-Reducing Measures

- **Gentle tactile stimulation** (neck or flank stroking before milking) promotes oxytocin release and counteracts cortisol-mediated inhibition of rumen activity.
- **Electrolyte–energy water** prepared with jaggery and salt supports rumen microbes and helps restore appetite, especially after transport.
- **Visual and environmental calming measures**, such as hanging green foliage in sheds, reduce heart rate and stress perception.

Routine Management Practices

- Adequate floor space (10–12 sq ft per animal)

- Increased feeding frequency with smaller meals
- Calm milking routines and reduced noise levels

Field-based trials in cooperative dairy systems have demonstrated that these interventions can restore most of the lost feed intake within 48 hours, leading to measurable economic gains.

Supporting the Rumen Microbiome

Maintaining microbial stability is essential for gut–brain balance. Locally available options such as fresh curd, fermented fodder, and gradual dietary transitions help rebuild beneficial microbial populations. Avoiding unnecessary antibiotic use is equally important, as it can exacerbate dysbiosis and prolong recovery.

Table 1: Stress-Rumen Impact Matrix

Stressor	Cortisol ↑ (%)	Rumen Motility ↓ (%)	Feed Intake ↓ (%)	Milk Loss (liters/day)
Heat (>35°C)	200	30	20-30	2-4
Rough handling	150	25	15-25	1-3
Transport (4+hrs)	300	40	25-40	3-5
Overcrowding	100 (chronic)	20	10-20	1-2

Table 1: Quantitative effects of common stressors on rumen function and production (adapted from field studies)

Conclusion

Stress-induced disruption of the gut–brain axis provides a scientific explanation for sudden feed refusal in farm animals despite adequate fodder availability. Through hormonal, neural, and microbial pathways, stress effectively suppresses rumen function and appetite. Indian dairy farmers can mitigate these effects using simple, affordable, and evidence-based management practices focused on reducing stress and supporting rumen health. By recognizing and addressing the gut–brain connection, farmers can improve feed intake, enhance milk production, and promote better animal welfare. This physiological understanding transforms routine management into a powerful tool for sustainable dairy productivity.

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THE SEED PARADOX: WHY INDIA'S QUEST FOR ATMANIRBHARTA IN PULSES AND OILSEEDS IS DEVOID OF SCIENCE

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Abstract

India's pursuit of self-reliance in pulses and oilseeds exposes a critical disconnect between financial ambition and scientific investment. While recent missions under *Atmanirbhar Bharat* commit over ₹21,000 crore to procurement, distribution, and infrastructure, they underfund the foundational agricultural research needed for long-term resilience. The prevailing strategy prioritizes area expansion and input subsidies over productivity-led innovation. Persistently low investment in agri-R&D—around 0.3% of agricultural GDP—contrasts sharply with global leaders like Brazil, China, and the US. This imbalance limits the development of climate-resilient, high-yielding, and short-duration varieties essential for a warming, volatile climate. Climate shocks in recent years underscore the cost of reactive rather than anticipatory research. Without major advances in genomics, speed breeding, and value-chain science, yield gaps will persist. Procurement-driven security cannot substitute for technological competitiveness. True *Atmanirbharta* demands a shift from buying output to building scientific capability. Investing in agricultural science today is essential to avoid deeper import dependence tomorrow.

Keywords: Atmanirbhar Bharat, Pulses and Oilseeds, Climate-Resilient Crops, Productivity Gap, Import Dependency, Agri-Innovation

The Grand Ambition vs. The Microscopic Reality

India stands at a critical agricultural crossroads, facing a paradox of plenty and scarcity. While the country has achieved a "Green Revolution" in cereals, its reliance on foreign soil for protein and fats remains an Achilles' heel. Under the expansive umbrella of *Atmanirbhar Bharat*, the Union Cabinet recently greenlit a legislative and financial fortress: the Mission for Aatmanirbharta in Pulses (2025-31) with an outlay of ₹11,440 crore, and the National Mission on Edible Oils (NMEO-Oilseeds) with ₹10,103 crore.

On the surface, these figures represent a historic commitment to ending the "Import Dependency" that drains billions in foreign exchange annually. However, a forensic look at the fine print reveals a worrying structural flaw: the strategy is overwhelmingly heavy on distribution and procurement—essentially "buying" domestic production—while remaining dangerously light on the high-end, foundational research required to survive an increasingly hostile climate. We are attempting to build a 21st century agricultural superpower using the financial blueprints of the 1970s.

The Strategy: Distribution Over Discovery

The current missions are built on a "quantity-first" philosophy. The government's primary levers for change are Area Expansion and Input Subsidies. The roadmap involves distributing 88 lakh free seed

kits (minikits) and bringing roughly 35-40 lakh hectares of "rice fallows" (land left idle after the rice harvest) under cultivation.

The Fallacy of 'More Land'

On paper, expanding acreage seems logical. In reality, the core problem of Indian pulses and oilseeds isn't a lack of land; it is stagnant productivity. For decades, pulses have been pushed to marginal, rainfed, and nutrient-poor lands because the "prime" irrigated land is occupied by the wheat-paddy cycle. If we move a 15-year-old seed variety to a new piece of land, we are simply scaling inefficiency. The yield gap—the difference between what a scientist achieves in a test plot and what a farmer gets in a village—is currently between 30% and 50%. No amount of free seed kits can bridge this if the seeds themselves are genetically exhausted or ill-equipped for the "new normal" of 2026 weather patterns.

The Funding Skew

Current estimates suggest that nearly 80% of the mission outlays are earmarked for:

Price Support: Guaranteeing 100% procurement at MSP for crops like Tur, Urad, and Masoor.

Physical Infrastructure: Building 1,000 localized processing units and storage silos.

Logistics: Moving seeds from government warehouses to remote blocks.

While these are necessary for farmer welfare, they are "defensive" expenditures. They protect the status quo but do not innovate. The "Research Slice"—the funding for high-end genomic mapping, CRISPR-Cas9 interventions for drought resistance, and the development of "heat-neutral" mustard—remains a rounding error in the total budget.

The "0.3% Trap": A Global Comparison

The most damning evidence of India's under-investment in science is the "Agri-R&D Intensity" ratio. For over two decades, India's investment in Agricultural Research and Education (via DARE and ICAR) has hovered around 0.3% to 0.4% of its Agricultural GDP.

How We Stack Up Against the World

Brazil: Often cited as the ultimate success story in oilseeds, Brazil spends nearly 0.8% to 1.0% of its agri-GDP on R&D. Through its research agency, Embrapa, Brazil transformed the acidic soils of its Cerrado region into a global soybean engine. They didn't just give farmers seeds; they re-engineered the soil and the plant.

China: With a similar smallholder farmer demographic as India, China invests roughly 0.62% in research. This has led to massive breakthroughs in hybrid rapeseed and soybean varieties that significantly outperform Indian averages.

High-Income Nations: Countries like the US and Canada invest between 2.0% and 3.0%. This is why a Canadian lentil farmer can produce three times the yield of an Indian farmer with half the water.

The DARE Deficit

In the 2025-26 Union Budget, while the overall Ministry of Agriculture saw a double-digit percentage boost, the DARE (Research) budget grew by a meager 3.1%. In real terms, when adjusted for inflation and the rising cost of scientific equipment, this is effectively a stagnant budget. We are asking our scientists to solve the protein crisis of 1.4 billion people with the budget of a mid-sized IT firm.

Climate Change: The Research Gap's New Best Friend

The years 2024 and 2025 served as a brutal laboratory for what happens when science lags behind climate. Terminal heat—sudden spikes in temperature during the pod-filling stage—decimated pulse yields across Madhya Pradesh. In Rajasthan, mustard crops were hit by erratic frost and then unseasonal rain.

Anticipatory vs. Reactive Research

Current Indian research is mostly reactive. We develop a variety to resist a pest that has already caused damage for five years. What we lack is Anticipatory Research.

Speed Breeding: We need facilities that can condense the 8–10 year breeding cycle into 3–4 years using controlled environments.

Short-Duration Varieties: To truly exploit "rice fallows," we need 60-day or 70-day pulse varieties that can grow on residual moisture before the heat of March kills the plant.

Bio-fortification: Research into increasing the oil content of seeds from 35% to 45% would effectively increase production by 10% without adding a single new acre of land.

Without a massive budgetary infusion into these specific niches, the goal of 350 lakh tonnes of pulses by 2030 will likely remain a mirage, pursued by farmers using 2015-era genetics in a 2026 climate.

The Policy Blind Spot: The Economic Science of Choice

Science isn't just about biology; it's about the economics of the field. Currently, a farmer in Punjab or Haryana looks at a pulse crop and sees "Risk." They look at Paddy and see "Certainty."

The Relative Profitability Gap

Research into the "Value Chain" is almost non-existent. Pulses and oilseeds are inherently "shatter-prone" and susceptible to storage pests.

Post-Harvest Research: We need decentralized, solar-powered "Dal Mills" that can be operated by Women's Self-Help Groups (SHGs).

Market Intelligence: There is a dismal lack of funding for real-time satellite-based yield forecasting, which would prevent the "boom and bust" price cycles that ruin farmers.

If the "cost of production" for an Indian farmer remains high due to low yields, even a high MSP cannot save them. The government cannot afford to buy every single grain at a premium forever. The only sustainable solution is to lower the cost of production through technology, making Indian oilseeds competitive with the cheap palm oil flowing from Indonesia and Malaysia.

The Human Capital Crisis in Research

Beyond the money, there is the matter of the "Mindset." A dismal funding environment leads to "Brain Drain." India's brightest agricultural biotechnologists are often found in the labs of St. Louis or Wageningen because Indian research centers lack the "Core Research Grant" (CRG) stability.

The Atmanirbhar missions focus on "Seed Kits" for farmers, but they forget the "Research Kits" for scientists. Our labs are often understaffed, and the administrative burden on scientists prevents the deep, focused work required for genetic breakthroughs.

Conclusion: From Procurement to Progress

The Atmanirbhar Bharat missions for pulses and oilseeds are well-intentioned and financially bold in their scope for market intervention. They have successfully addressed the "Fear Gap" by promising to buy what the farmer grows. However, Procurement is not Progress. True self-reliance (Atmanirbharta) will not be achieved by building a taller wall of import duties or a larger warehouse of subsidized grain. It will be achieved when an Indian pulse variety is so resilient, high-yielding, and profitable that a farmer in the Kaveri delta or the Indo-Gangetic plain chooses it over rice—not because of a government kit, but because of scientific superiority. Until the national budget reflects this scientific ambition—shifting from a 0.3% R&D spend to a minimum of 1.0%—our quest for self-sufficiency will remain a costly import-substitution exercise. We are currently funding the "body" of Indian agriculture while starving its "brain." If we do not fund the science today, we will be paying for the imports tomorrow.

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TINY CREATURES, POWERFUL NUTRITION: INSECTS AS HUMAN FOOD

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Abstract

As the global population continues to grow and environmental pressures on conventional food systems intensify, the search for sustainable, nutritious, and affordable food sources has become increasingly important. Insects, long regarded as pests or unconventional foods, are now gaining scientific and public attention as a viable component of the human diet. This popular article explores the concept of entomophagy—human consumption of insects—highlighting its historical roots, global cultural acceptance, and strong scientific foundation. Edible insects are rich in high-quality protein, essential amino acids, healthy fats, vitamins, and minerals, while requiring significantly fewer natural resources than traditional livestock. The article also discusses environmental advantages, food safety considerations, and the cultural barriers that limit wider acceptance of insect-based foods. By combining traditional knowledge with modern nutritional science, this article argues that insects have the potential to contribute meaningfully to future food security and sustainable diets, offering a practical and environmentally responsible solution to global nutritional challenges.

Keywords : Edible insects; Entomophagy; Sustainable food; Alternative protein; Human nutrition; Food security; Climate-friendly diet; Insect-based food

Introduction

As the global population moves rapidly toward nine billion, the question of *what we will eat tomorrow* has become more urgent than ever. Rising food demand, shrinking agricultural land, climate change, and the high environmental cost of meat production are forcing scientists and policymakers to rethink conventional food systems. While plant-based diets and laboratory-grown meat receive much attention, one highly nutritious and sustainable food source remains largely ignored by many societies—insects. For centuries, insects have been viewed primarily as pests or disease carriers. However, this perception overlooks an important reality: insects have been part of the human diet long before modern agriculture began. Today, they are being rediscovered not as survival food, but as a scientifically validated source of nutrition with significant environmental benefits. According to the Food and Agriculture Organization (FAO), edible insects could play an important role in addressing global food insecurity, malnutrition, and environmental sustainability (FAO, 2013). Insects are small in size, yet rich in protein, vitamins, and minerals. They require fewer natural resources to produce compared to traditional livestock and generate lower greenhouse gas emissions. In a world searching for sustainable solutions, insects may represent a bridge between ancient food traditions and modern nutritional science.

Entomophagy: An Ancient and Global Practice

The consumption of insects, known as *entomophagy*, is not a new or unusual practice globally. Anthropological studies reveal that insects are traditionally consumed in more than 100 countries

across Africa, Asia, Latin America, and Oceania (van Huis *et al.*, 2013). It is estimated that over two billion people worldwide include insects in their regular diets (FAO, 2013). Commonly consumed insects include grasshoppers, crickets, termites, beetle larvae, ants, and silkworm pupae. In India, silkworm pupae are eaten in parts of the Northeast; in Mexico, chapulines (grasshoppers) are popular snacks; and in Thailand, fried crickets are widely available street food. These examples highlight that entomophagy is culturally normal in many societies and only appears “strange” where it has been historically absent.

Nutritional Value: Small Body, Big Benefits

Edible insects are highly nutritious. Numerous studies show that insects provide high-quality **protein**, often comparable to beef, chicken, and fish (Rumpold & Schlüter, 2013). On a dry-weight basis, many insects contain between 40–70% protein and offer a balanced profile of essential amino acids.

In addition to protein, insects are rich in:

Healthy fats, including polyunsaturated fatty acids

Micronutrients such as iron, zinc, calcium, and magnesium

Vitamins, especially B-complex vitamins including B12

Insects also contain chitin, a form of dietary fibre that may support gut health. Research suggests that consuming insects could help combat protein-energy malnutrition and micronutrient deficiencies, particularly in vulnerable populations such as children and pregnant women (Payne *et al.*, 2016).

Environmental Sustainability of Insect Consumption

One of the strongest arguments for insects as food is their low environmental footprint. Compared to conventional livestock, insects require significantly less land, water, and feed. They are highly efficient at converting feed into edible body mass, a characteristic known as high feed conversion efficiency (Smetana *et al.*, 2016). For example, producing one kilogram of cricket protein requires far less feed than producing one kilogram of beef protein. Insects also emit fewer greenhouse gases such as methane and ammonia, making them more climate-friendly. Life-cycle assessment studies consistently show that insect farming can reduce environmental pressure when compared with traditional meat production (Oonincx & de Boer, 2012).

Food Safety and Health Aspects

As with any food source, edible insects must meet food safety standards. Potential risks include microbial contamination, chemical residues, and allergic reactions—particularly for individuals allergic to shellfish due to protein similarities (Rumpold & Schlüter, 2013).

However, these risks can be effectively managed through:

Controlled rearing conditions

- Hygienic processing
- Proper cooking methods such as roasting, boiling, or drying

FAO and food safety authorities emphasize that insects produced under regulated conditions are as safe for consumption as conventional animal products (FAO, 2013).

Cultural Acceptance: The Main Barrier

Despite strong nutritional and environmental evidence, consumer acceptance remains a major challenge, especially in Western and urban societies. Disgust and psychological resistance are the main barriers rather than scientific concerns. Interestingly, studies show that acceptance increases

when insects are processed into familiar food forms such as flour, protein bars, biscuits, or pasta (Hartmann *et al.*, 2015). Education, exposure, and positive messaging are essential to shift public perception and normalize insect-based foods.

Insects in the Modern Food System

Today, insect-based foods are gradually entering global markets. Cricket flour, mealworm protein, and insect-based snacks are being developed by food startups worldwide. Some countries have formally approved insect species for human consumption, encouraging innovation and commercialization. Beyond direct consumption, insects are also being used as sustainable feed for poultry and fish, indirectly improving human food systems.

Conclusion

Insects are no longer just creatures that crawl under our feet or damage crops—they are emerging as nutritional allies in the fight against hunger and environmental degradation. Rich in protein, minerals, and healthy fats, insects offer a sustainable and efficient food source that complements existing diets. While cultural resistance remains a challenge, scientific evidence and traditional knowledge strongly support the inclusion of insects in future food systems. As the world looks for smarter ways to nourish humanity without exhausting the planet, embracing these tiny creatures may be a powerful step forward.

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TRICHOCAKE: A SUSTAINABLE BIOCONTROL FORMULATION USING *Trichoderma* spp. FOR MANAGING COCONUT BUD ROT AND OTHER FUNGAL DISEASES

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Abstract

Trichocake, a novel biocontrol formulation utilizing *Trichoderma harzianum* integrated with coir pith, offers a sustainable solution for managing fungal diseases in tropical crops, notably coconut bud rot caused by *Phytophthora palmivora*, stem bleeding, *Ganoderma* wilt, and cocoa stem canker. By leveraging the coconut industry's lignocellulosic waste, this eco-friendly product exemplifies circular economy principles, reducing reliance on chemical fungicides that pose environmental and health risks. Trichocake employs multiple mechanisms like mycoparasitism, antibiosis, nutrient competition, systemic resistance induction, and plant growth promotion to achieve disease reductions of 50-70%, as demonstrated in field trials across regions such as Kasaragod. With a shelf life of 10 months and a viable *T. harzianum* population of 5×10^6 cfu/g, it ensures scalability and accessibility for farmers. Beyond disease control, Trichocake enhances soil health, increases nutrient availability, and improves plant resilience to abiotic stresses, thereby contributing to sustainable agriculture and food security.

Key words: Biocontrol, Bud rot, Coirpith, Sustainability, Trichocake

Introduction

The escalating global population necessitates an enhanced demand for both quantity and quality in food production. It was estimated that food production needs to increase by 50% to feed the projected 9.3 billion people by 2050 (Wang *et al.*, 2024). But plant diseases become a serious threat to crop production and food security. More than 30% of annual crop yield loss was estimated globally, which is worth hundreds of billions of dollars (Gai & Wang., 2024). Fungal diseases like bud rot in coconut caused by *Phytophthora palmivora* pose severe threats, leading to 30-50% yield loss in endemic regions such as India, Srilanka, and the Pacific Islands (Coconut Development Board, 2024). The use of chemical fungicides shows effectiveness against the fungal pathogens, but it adversely affects the environment and is a threat to the life of organisms, including humans. They not only contaminate the soil and groundwater but also become detrimental to non-target organisms, accumulate residues, and develop resistance to these chemicals on long-term use. Among various strategies adopted against the ill effects of chemical fungicides, one of the most sustainable and eco-friendly methods is the use of Biocontrol Agents (BCA). These are living microorganisms or their metabolites that are utilized to suppress or reduce the population of plant pathogens (Tyskiewicz *et al.*, 2022). *Trichoderma* spp. are the most widely used biocontrol agents (about 60%) so far due to its different direct and indirect mechanisms of action. Mycoparasitism, antibiosis, competition for space and nutrients, and production of cell wall degrading enzymes are the direct mechanisms of *Trichoderma* spp. against plant pathogens. Whereas induction of plant defence through local or systemic plant resistance and plant growth promotion can be considered as an indirect mode of action of *Trichoderma* spp (Tyskiewicz *et al.*, 2022).

Trichoderma harzianum, isolated by the ICAR-Central Plantation Crops Research Institute (CPCRI), has emerged as a potent isolate for tropical crops. Trichocake or *Trichoderma* coir pith cake (TCPC) harnesses this strain in a solid matrix, transforming coconut industry waste -coir pith into a value-added product. This formulation not only curbs bud rot but also targets stem bleeding (*Thielaviopsis paradoxa*) and *Ganoderma* wilt in coconuts, alongside stem canker in cocoa. By integrating waste management with biological pest control, Trichocake exemplifies circular economy principles in agriculture (ChandraMohan et al., 2014).

Composition and Production of Trichocake

Trichocake's innovation lies in its simple, scalable production using readily available, low-cost materials: coir pith (a lignocellulosic byproduct from coconut husk defibering), maida flour as a nutrient binder, and *T. harzianum* broth as the active biocontrol agent. Coir pith, often discarded as waste, serves as an inert carrier with high water-holding capacity (8-9 times its weight), fostering *Trichoderma* proliferation while minimizing formulation costs.

Table 1 : Composition and role of each ingredients in Trichocake

Ingredients	Quantity per Batch (for ~16-17 cakes)	Role
Coir pith	500 g (moistened to 70-75% moisture)	Carrier substrate: provides structure and nutrients
Maida flour	70 g (boiled in 280 ml water)	Binding and nutrient source; forms sticky paste for cohesion
<i>T. harzianum</i> biomass slurry	100 ml (from potato-jaggery broth)	Active biocontrol agent; antagonistic spores and mycelia
Water	As needed for moistening and activation	Hydration for fungal growth

The production of Trichocake involves a series of meticulously controlled steps to ensure the viability and efficacy of the *Trichoderma harzianum* within a stable coir pith matrix. Initially, biomass preparation entails cultivating *T. harzianum* in 100 ml of potato-jaggery broth, formulated with 20 g of jaggery and 20 g of potato extract per 375 ml bottle, which is autoclaved at 15 psi for 20 minutes prior to inoculation with a 5 mm disc from a 3-day-old culture. The inoculated broth is then incubated at 26-30°C for 7 days in a slanted position to optimize surface area for fungal growth, followed by homogenization of the fungal biomass with the spent medium for 1-2 minutes to produce a uniform slurry.

Concurrently, coir pith sterilization begins with the removal of long fibers from fresh coir pith, moistening it to 70-75% moisture content, and packing 500 g into polypropylene bags measuring 45 x 30 cm, which are autoclaved at 20 psi for 30 minutes and allowed to cool to room temperature. Maida paste formation follows, where 70 g of maida is boiled in 280 ml of water to create a thick, sticky paste serving as both an adhesive and a carbon source. The subsequent mixing and molding phase occurs in a sterile tray, where the sterilized coir pith is blended with the *Trichoderma* slurry and maida paste; portions of 30 g are then measured and manually compressed using a simple press, such as a metallic cylinder of 4.5 cm diameter, to form solid cakes on a plastic sheet. Finally, drying and packaging involve oven-drying the cakes at 38-40°C for 4 days with initial ventilation to facilitate moisture evaporation, after which the dried cakes are packed in polythene bags and stored at 26-30°C to maintain shelf stability.

This process yields cakes with an initial *T. harzianum* population of $\sim 10^7$ - 10^8 cfu/g. Shelf life extends to 10 months at room temperature, retaining 5×10^6 cfu/g, with populations surging to 14.4×10^6 cfu/g upon activation (moistening with 18-20 ml water and incubating for 2 days). The technology, patented by CPCRI, has been transferred to various private and public firms, enabling farmer-level production (ChandraMohanana *et al.*, 2014).

Mechanisms of Action

Mycoparasitism: *T. harzianum* directly attacks pathogen hyphae by coiling around them, penetrating cell walls, and releasing lytic enzymes (e.g., chitinases and β -1,3-glucanases) to degrade and absorb nutrients from the pathogen, leading to its death.

Antibiosis: The fungus produces secondary metabolites, antibiotics, and antifungal compounds (e.g., harzianic acid, gliotoxin, and peptaibols) that inhibit pathogen growth and spore germination by creating a toxic environment.

Competition for Nutrients and Space: *T. harzianum* rapidly colonizes the rhizosphere or plant tissues, outcompeting pathogens for essential resources like iron (via siderophores), space, and nutrients, while also acidifying the soil to favor its own growth.

Induction of Systemic Resistance: It triggers plant defense responses by releasing elicitors (e.g., chitin oligosaccharides), activating enzymes like peroxidase and phenylalanine ammonia-lyase, which enhance the host plant's innate immunity against infections.

Plant Growth Promotion: Indirectly supports biocontrol by solubilizing nutrients (e.g., phosphates) and producing phytohormones, improving plant health and resilience to make it less susceptible to diseases (Yao *et al.*, 2023).

Application Methods

As per the recommendations from CPCRI, Kasaragod, two activated trichocakes can be placed on either side of the growing bud of coconut at a bimonthly interval from June to December, along with crown cleaning for the management of bud rot. Placing of moistened TCPC by tying it onto the bark of the stem bleeding affected coconut trees after the removal of bleeding patches, and against the stem canker in cocoa by *Lasiodiplodia theobromae* are also practiced in many fields. It can also be used as other commercial products, for soil application by burying the cakes in the base of the plants and mixing the powdered cakes with potting mixture for seedling protection (Coconut Development Board, 2024).

Efficacy and Field Trials

Field evaluations across budrot hotspot regions like Kasaragod underscore the reduced disease incidence and severity by 50-70% (Prathibha *et al.*, 2023). Studies conducted by Neeraja, B. *et al.*, (2020) on the management of stem bleeding of coconut show that the use of trichocakes completely brought down the disease index from 12.91% to 0% within 50 days of cake application, and also there was a significant increase in the nut yield. In cocoa, Trichocake curbed stem canker by 75%, with *T. harzianum* populations persisting at 10^6 CFU/g in soil for 6 months. These results, from CPCRI and Kerala Agricultural University trials, highlight its consistency across agro-climatic zones (Peter & Chandra Mohanana, 2014).

Similarly, many research works highlight the potential of *T. harzianum* as an antagonist against common phytopathogens, such as *Fusarium* spp., *Phytophthora* spp., *Rhizoctonia* spp., *Colletotrichum* spp., *Phoma* spp., *Pythium* spp., and *Sclerotinia sclerotiorum*, among others. This

marks the significance of cheaper and environmentally friendly bioformulations, like trichocake (Woo *et al.*, 2020).

Benefits of Trichocakes

Besides disease control, *T. harzianum* has multifaceted significance in sustainable agriculture. *T. harzianum* in Trichocake produces hormone-like compounds (e.g., auxins, gibberellins) that stimulate root development and overall plant vigour. In tomato and cucumber trials, it mitigated abiotic stresses like salt and drought, increasing biomass by 20-30% via enhanced nutrient mobilization. Trichocake enhances soil organic matter and microbial diversity by decomposing lignocellulosic substrates like coir pith and increases the soil water holding capacity by 8-10 times its weight (Thomas *et al.*, 2018). The fungus solubilizes phosphates, iron, and other minerals, improving nutrient availability and also aids in the bioremediation of contaminated soils (Chen *et al.*, 2025 & Woo *et al.*, 2020). Recent studies show that its benefits expand to insect pests and nematode control directly or indirectly (Poveda J., 2021 & Yao *et al.*, 2023).

Conclusion

Trichoderma spp., first identified as a biocontrol agent in the 1930s by Weindling, has fundamentally reshaped sustainable agriculture through its robust antagonism toward plant pathogens, establishing a cornerstone for eco-friendly disease management. Trichocake, an innovative formulation that harnesses *T. harzianum* with coir pith, exemplifies sustainable ingenuity by converting coconut industry waste into a powerful tool against diseases like bud rot, while delivering additional benefits. It significantly reduces reliance on chemical pesticides in field applications, acts as a biostimulant to enhance plant growth by improving nutrient uptake and resilience to abiotic stresses such as drought and salinity, promotes soil health by boosting microbial diversity and organic matter decomposition, and supports bioremediation by degrading pollutants like hydrocarbons. Looking forward, advancing Trichocake's potential requires research into genomic enhancements for broader pathogen control and climate adaptability, scalable production models to empower smallholder farmers, and integration with microbial consortia to tackle pressing challenges in global food security and environmental sustainability.

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USAGE OF SOLAR ENERGY IN AGRICULTURE: APPLICATIONS, STATUS AND PROSPECTS IN INDIA

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Abstract

The increasing pressure on agricultural systems to meet rising food demand, coupled with escalating energy costs and environmental concerns, has intensified the need for sustainable energy solutions in agriculture. In India, agriculture is highly dependent on fossil fuels and grid electricity for irrigation, mechanization, processing and post-harvest operations, which contributes to greenhouse gas emissions and economic vulnerability of farmers. Solar energy, as a clean, renewable and abundantly available resource, offers a viable alternative to conventional energy sources. This article reviews the present status of solar energy in India and examines its diverse applications in the agricultural sector, including solar water pumping systems, solar dryers, solar fencing, solar sprayers, solar tractors, agrivoltaic farming and other emerging technologies. The study concludes that widespread adoption of solar energy can significantly reduce production costs, enhance energy security, improve farm sustainability and contribute to climate-resilient agricultural development in India.

Keywords: Solar energy; Sustainable agriculture; Renewable energy; Agrivoltaic farming; Solar irrigation;

Introduction

India, with a population exceeding 1.4 billion, faces an ever-increasing demand for food, energy and natural resources. Agriculture remains the backbone of the Indian economy, providing livelihood to a significant share of the population. However, the sector is confronted with serious challenges such as climate change, soil degradation, water scarcity, rising input costs and heavy dependence on fossil fuels. Conventional energy sources used in agriculture-diesel and grid electricity-contribute substantially to greenhouse gas emissions and increase production costs for farmers.

Non-renewable energy sources emit greenhouse gases that trap solar radiation in the atmosphere, leading to global warming and climate change. In this context, the transition towards renewable energy sources has become a priority for sustainable agricultural development. Solar energy being abundant clean and renewable offers immense potential to address energy needs in agriculture while reducing environmental impacts. India's geographical location provides high solar irradiation for most of the year, making solar energy a viable alternative for powering agricultural operations.

In alignment with the Sustainable Development Goals (SDGs), India's power generation mix is rapidly shifting towards renewable energy. The integration of solar energy into agriculture has the potential to revolutionize farming systems by reducing dependence on fossil fuels, lowering operational costs, enhancing energy security and generating additional income opportunities for farmers (Santosh *et al.*, 2023).

Problems Associated with Non-Renewable Energy Sources

The extensive use of non-renewable energy sources in agriculture has led to several economic and environmental concerns. Fossil fuels are finite and subject to price volatility, which directly affects the cost of cultivation. Diesel-powered irrigation pumps and machinery contribute to air pollution and carbon emissions. Moreover, dependence on grid electricity often results in unreliable power supply, particularly in rural areas. These limitations highlight the urgent need for cleaner and more sustainable energy alternatives in agriculture (Kazar's Electric, 2022).

Benefits of Solar Energy in Agriculture

The adoption of solar technologies in agriculture offers multiple advantages. Solar energy is environmentally friendly and significantly reduces greenhouse gas emissions. It is a reliable and cost-effective energy source in the long run, as sunlight is freely available and operating costs are minimal after installation. Solar technologies promote energy independence, reduce expenditure on fuel and electricity and create employment opportunities in rural areas through installation, maintenance and manufacturing of solar systems (EmPower Solar, 2021).

Present Scenario of Solar Energy in India

India has emerged as one of the leading countries in solar power deployment. According to the International Renewable Energy Agency and the Central Electricity Authority (CEA), India's installed power generation capacity has crossed ~509.64 GW, with renewable energy sources contributing ~253.96 GW. Solar energy accounts for a rapidly growing share of this capacity. The agriculture sector is also witnessing a steady increase in electricity consumption, emphasizing the importance of integrating renewable energy solutions such as solar power to meet rising demand sustainably (IRENA, 2025).

Several states, including Gujarat, Rajasthan and Karnataka, are leading in solar installed capacity. Gujarat, in particular, has made notable progress through large-scale solar projects and farmer-oriented solar initiatives supported by state agencies.

Applications of Solar Energy in Agriculture

Solar Water Pumping Systems

Solar water pumping systems are among the most widely adopted solar technologies in agriculture. These systems consist of photovoltaic panels and motor-pump sets that convert solar energy into electricity for irrigation. Solar pumps offer advantages such as zero fuel cost, long operational life, low maintenance, ease of operation and environmental friendliness (Eker, 2005; Saxena & Kumar, 2021). They are particularly beneficial in remote areas where grid electricity is unreliable or unavailable.

Solar Fencing Systems

Solar fencing systems function as electric fences powered by solar energy, delivering mild but effective shocks to deter animals without causing harm. These systems help protect crops from wild animals and reduce crop losses while ensuring safety for both humans and animals (Vahedi, 2017).

Solar Sprayers

Solar-powered pesticide sprayers are designed to enhance the productivity of small and marginal farmers. These lightweight machines can operate directly using solar energy during daytime, reducing dependence on batteries and manual labour. They are cost-effective, easy to handle and environmentally friendly (Vahedi, 2017).

Solar Dryers

Solar dryers are used for preserving agricultural produce by removing moisture, thereby extending shelf life and reducing post-harvest losses. Compared to open-air drying, solar dryers provide faster, more uniform drying and better product quality. They save energy, time and space while improving overall efficiency (Vahedi, 2017).

Solar Tractors

Solar tractors operate using electricity generated from solar panels and stored in battery systems. They eliminate the need for internal combustion engines, thereby reducing emissions and fuel costs. Solar tractors offer a sustainable alternative for farm mechanization, particularly for small and medium-scale farming systems (Mousazadeh *et al.*, 2011).

Solar Insect and Pest Traps

Solar insect traps use ultraviolet light powered by solar energy to attract and capture pests. These systems operate automatically and help reduce crop damage while minimizing the use of chemical pesticides (Times of Agriculture, 2023).

Solar Milking Machines

Solar-powered milking machines assist dairy farmers by enabling faster and more hygienic milking operations. These machines reduce drudgery, increase milk yield and quality and allow farmers to manage larger herd sizes efficiently (Times of Agriculture, 2023).

Solar Greenhouses

Solar greenhouses utilize solar energy for heating and lighting, reducing dependence on fossil fuels. These structures are designed to capture and store heat, enabling crop production even during unfavourable climatic conditions (Vahedi, 2017).

Solar Lighting and Agrivoltaic Farming

Solar lighting systems are used to supplement light for crops such as dragon fruit, enhancing photosynthesis and productivity. Agrivoltaic farming involves growing crops beneath elevated solar panels, allowing simultaneous production of food and energy. Studies indicate that certain crops perform equally well or better under partial shading, improving land-use efficiency and resilience to climate stress (World Economic Forum (WFM), 2022).

Role of Government and Policy Support

The Government of India plays a crucial role in promoting solar energy through policies, subsidies and schemes implemented by the Ministry of New and Renewable Energy (MNRE, 2022). India aims to achieve 40 percent of its installed electric capacity from non-fossil sources by 2030. Government initiatives such as solar pump schemes and grid-connected solar programs have encouraged farmers to adopt solar technologies and even sell surplus power to the grid.

Conclusion

Solar energy presents a promising and sustainable solution to meet the growing energy demands of Indian agriculture. Its adoption can significantly reduce production costs, enhance energy security,

mitigate environmental impacts, and contribute to rural development. With strong policy support, technological advancements and increased awareness among farmers, solar energy can play a transformative role in achieving sustainable agricultural growth and a greener future for India.

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USE OF IoT, SENSORS AND MOBILE APPS FOR FRUITS AND VEGETABLES STORAGE AND TRANSPORT

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Summary

The article highlights the role of IoT-based sensors, smart packaging and mobile applications in improving the storage and transportation of fruits and vegetables. Real-time monitoring of temperature, humidity and gases helps maintain quality, extend shelf life and reduce post-harvest losses. The integration of machine learning enhances prediction accuracy and decision-making, while smart packaging and mobile apps improve traceability and user control. Despite challenges such as high costs and lack of standardization, the article concludes that IoT technologies offer a promising, sustainable solution for safer and more efficient fresh produce supply chains.

Introduction

The integration of IoT, sensors and mobile applications in the storage and transportation of fruits and vegetables is a burgeoning field aimed at enhancing food safety, quality and reducing waste. These technologies enable real-time monitoring and control of environmental conditions, which are critical for maintaining the freshness and nutritional value of perishable produce. The literature highlights various approaches and technologies that have been developed to address these challenges, focusing on IoT-enabled sensor networks, smart packaging and mobile applications. Below, the key aspects of these technologies are discussed in detail.

IoT-Enabled Sensor Networks

IoT-enabled sensor networks are pivotal in monitoring critical environmental parameters such as temperature, humidity and gas concentrations during the transportation and storage of fruits and vegetables. These parameters significantly affect the quality and shelf life of produce (Kumar & Sharma, 2024) (Lamberty & Kreyenschmidt, 2022). Implementing these sensor networks can lead to improved decision-making and proactive management of environmental conditions, thereby minimizing the risk of spoilage and waste (Lamberty & Kreyenschmidt, 2022). Moreover, the application of IoT-enabled sensor technology can facilitate real-time data exchange, allowing stakeholders to respond swiftly to any deviations from optimal storage conditions, thus enhancing overall food safety and quality (Lamberty & Kreyenschmidt, 2022).

The use of machine learning algorithms, such as Support Vector Machine (SVM), enhances the accuracy of these systems in predicting and maintaining optimal storage conditions. SVM has been shown to outperform other algorithms with an accuracy of 98.05% in some studies (Kumar & Sharma, 2024) (Satyaraj *et al.*, 2024). This integration of IoT and machine learning not only optimizes food storage but also contributes to reducing food waste and improving sustainability in the agricultural sector.

IoT architectures facilitate seamless communication between sensors, actuators and command centers, allowing for dynamic adjustments to storage conditions based on real-time data (Satyaraj

et al., 2024). This adaptability is crucial for ensuring that fruits and vegetables are stored under optimal conditions, ultimately extending their shelf life and reducing waste.

Smart Packaging

Smart packaging technologies incorporate advanced sensors and materials to monitor and regulate the storage environment of fruits and vegetables. This approach extends shelf life, enhances food safety and reduces waste by automatically adjusting internal conditions to slow bacterial growth and retain nutritional content (Du *et al.*, 2025). These technologies also foster increased transparency and traceability in the supply chain, ensuring that consumers receive high-quality, safe products while minimizing environmental impact (Gaikwad & Anerao, 2025).

Despite its potential, the widespread adoption of smart packaging is hindered by high costs, limited material diversity and lack of standardization. However, ongoing advancements in technology and material innovation are expected to overcome these challenges (Du *et al.*, 2025). As the industry evolves, addressing these barriers will be essential for maximizing the benefits of smart packaging and ensuring its successful integration into the food supply chain.

Mobile Applications

Mobile applications, often integrated with IoT systems, provide users with real-time data on environmental conditions affecting food quality. These apps can alert users to changes in conditions and suggest corrective actions (Survey on IoT Based Farm Freshness Mobile Application, 2022) (Srivastava & Gulati, 2016). These applications not only enhance user engagement but also empower stakeholders to make informed decisions, ultimately contributing to improved food safety and reduced waste.

An example is an Android application that uses sensors to monitor temperature, humidity, and other factors, providing real-time notifications and analysis to users. This app also includes features like a chatbot for food quality information and location-based store suggestions (Survey on IoT Based Farm Freshness Mobile Application, 2022) (Swathi *et al.*, 2022). The integration of these technologies is crucial for creating a more resilient and efficient food supply chain that prioritizes safety and sustainability.

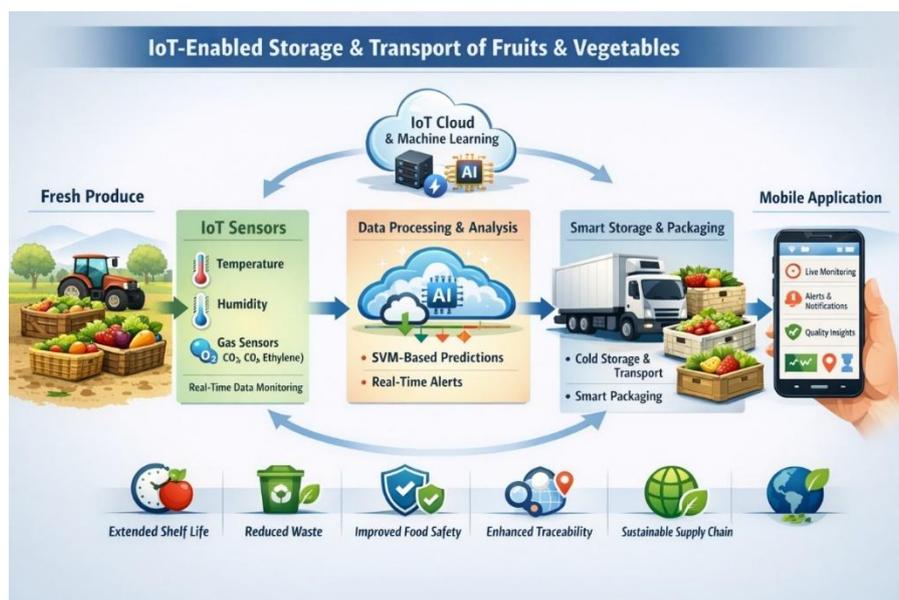


Fig.1: Integration of IoT sensors, smart packaging, machine learning, and mobile applications for real-time monitoring and quality preservation of fruits and vegetables during storage and transportation

Challenges and Future Directions

While IoT and sensor technologies offer significant benefits, their large-scale implementation in the fresh produce supply chain faces challenges such as high costs, technical complexity, and the need for standardization (Lamberty & Kreyenschmidt, 2022) (Dias *et al.*, 2021). To address these challenges, collaboration among industry stakeholders, investment in research and development and the establishment of clear standards will be vital for the successful integration of these technologies into the food supply chain.

Future research and development are likely to focus on improving the integration of IoT with big data analytics, developing environmentally sustainable packaging solutions, and enhancing the scalability and adaptability of these technologies (Du *et al.*, 2025) (PU, n.d.). By leveraging these advancements, stakeholders can enhance food safety, reduce waste and ultimately contribute to a more sustainable food supply chain.

Conclusion

The use of IoT, sensors and mobile applications in the storage and transportation of fruits and vegetables presents a promising solution to enhance food safety and reduce waste. However, the successful implementation of these technologies requires overcoming several challenges, including cost, complexity and standardization. As technology continues to advance, these barriers are expected to diminish, paving the way for more efficient and sustainable food supply chains.

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SMART MULCHES THAT CONTROL SOIL TEMPERATURE AND MOISTURE: ENHANCING CROP PRODUCTIVITY AND SUSTAINABILITY

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Abstract

Plant development, nutrient absorption, and yield all depend on the ideal soil temperature and moisture. Even if they are beneficial, conventional mulching methods frequently fall short in controlling these variables in climatically changeable environments. Soil microclimates may be precisely controlled with smart mulches such biodegradable films, reflecting mulches, moisture-retentive hydrogels, and temperature-sensitive materials. They promote climate-resilient agriculture, increase nutrient availability, decrease weeds, lessen insect pressure, and improve water usage efficiency. With an emphasis on useful tactics for farmers, extension agents, and agri-entrepreneurs worldwide, this article offers a thorough analysis of smart mulch technologies, their mechanisms, crop-specific applications, agronomic benefits, economic and environmental advantages, challenges, and future prospects.

Keywords: biodegradable films, hydrogels, reflecting mulches, soil temperature, soil moisture, smart mulches, water-use efficiency, climate-resilient agriculture, and sustainable farming.

Introduction

Among the most important variables influencing crop yield, nutrient absorption, root growth, and seed germination are soil temperature and moisture. Low soil temperatures hinder germination and decrease nutrient availability, whereas high soil temperatures can impede microbial activity and root development. In a similar vein, variations in soil moisture whether excessive or insufficient have an impact on photosynthesis, plant water relations, and eventually production and quality. Conventional mulches, including straw, residual agricultural materials, or black polyethylene films, have certain benefits in terms of moisture conservation and weed control. However, their effectiveness is sometimes limited by material degradation, uneven soil cover, and severe weather. Furthermore, conventional plastic mulches lead to environmental pollution and are challenging to dispose of. Smart mulches have developed as a solution that combines material science and agronomy to create mulching systems that may actively manage soil microclimate, improve crop development, conserve water, and minimize environmental effects.

Concept and Classification of Smart Mulches

Smart mulches are cutting-edge materials made to regulate soil temperature, hold onto moisture, inhibit weed growth, and occasionally affect insect behavior. In contrast to conventional mulches, they offer multipurpose advantages and are designed for particular crop and climate requirements.

Classification of Smart Mulches



Biodegradable Mulches: These are made from materials such as polylactic acid (PLA), starch blends, or cellulose, which naturally decompose in the soil. They help reduce plastic waste while providing the benefits of conventional mulching.



Reflective / Colored Mulches: White or silver films reflect solar radiation to lower soil temperature, whereas red or blue films can enhance fruit quality and help repel specific pests, improving crop performance and protection.



Moisture-Retentive Polymers (Hydrogels): These materials absorb and store water, releasing it slowly to plant roots. This reduces the frequency of irrigation and improves water-use efficiency, especially under water-limited conditions.



Temperature-Sensitive / Photodegradable Films: Designed to change reflectivity or degrade under sunlight exposure, these films help maintain optimal soil temperatures throughout the growing season.



Organic Smart Mulches: Made from treated straw, coir mats, or composted crop residues, these mulches retain soil moisture, supply nutrients, and enhance soil microbial activity, promoting healthier plant growth and soil fertility.

Figure 1. Types of Mulches Used for Soil Temperature and Moisture Regulation

Mechanisms of Action

Soil Temperature Regulation

Mulches help regulate soil temperature to create favorable conditions for plant growth. Reflective mulches reduce heat accumulation in hot soils by reflecting sunlight, preventing root stress and maintaining active soil microbial populations. Conversely, heat-retentive mulches absorb solar radiation in cooler climates, raising soil temperature to accelerate seed germination and early plant development. Temperature-modifying mulches also influence crop phenology, enhancing flowering and fruiting in sensitive crops such as strawberries and melons.

Preservation of Soil Moisture

By reducing water evaporation from the soil's surface, hydrophilic polymers and biodegradable coatings provide steady hydration in the root zone. Such mulches can improve water-use efficiency while promoting healthy crop development by reducing watering frequency by 20-40%, according to field tests in fruits and vegetables.

Suppression of Weeds

Mulches serve as a physical barrier that prevents weeds from growing. Some reflective coatings further impair the quality of light at the soil's surface, preventing light-sensitive weed seeds from germinating and lessening competition for water and nutrients.

Pest and Disease Management

Pest behavior can be influenced by colored mulches; for example, aphids are known to be repelled by silver films. Mulches encourage healthier plants with less chemical intervention by keeping the soil surface drier, which also lowers the frequency of fungal infections in crops vulnerable to soil-borne pathogens.

Nutrient Efficiency

By maintaining soil moisture and temperature, mulches increase the availability of nutrients by promoting microbial activity and nutrient mineralization. Additionally, they improve the efficiency of nitrogen absorption and promote sustainable crop production by reducing nutrient leaching during periods of high rainfall.

Crop-Specific Applications**Table 1 - Crop-wise Selection of Smart Mulches and Their Agronomic Benefits**

Crop Type	Smart Mulch Type	Benefit
Tomato/Capsicum	Black biodegradable film	Early germination, moisture retention, weed suppression
Strawberry	Red or reflective biodegradable mulch	Improved fruit color, yield, disease suppression
Melon/Watermelon	Silver reflective film	Lower soil temperature, pest repellence
Cotton/Chili	Heat-retentive or moisture-retentive mulch	Uniform growth, water efficiency
Vegetable beds	Hydrogels + biodegradable mulch	Reduced irrigation frequency, improved yield

Field Evidence

Black biodegradable mulch was found to boost tomato yields by 15–20% in trials conducted in China and India.

Due to increased anthocyanin concentration, strawberry fields with red mulch displayed 10–12% improved marketable fruit quality.

Practical Guidelines for Farmers

- **Mulch Selection:** To optimize advantages, select the type of mulch depending on soil characteristics, local climate, and crop requirements. While reflective or colorful films may be appropriate for some crops or pest control requirements, biodegradable or organic mulches are best for simple management.
- **Installation:** To avoid displacement by wind or irrigation, lay mulches in close proximity to the soil's surface, securely fasten the edges, and overlap sheets. Optimal performance and consistent soil covering are guaranteed by proper installation.
- **Integration with Irrigation:** To effectively supply water directly to the root zone, use drip or micro-sprinkler systems under mulches. This combination guarantees steady moisture availability and improves water-use efficiency.
- **Monitoring:** To adjust irrigation schedules and avoid water stress or excessive heat accumulation, periodically monitor the temperature and moisture content of the soil beneath the mulch.
- **Removal/Degradation:** Because biodegradable mulches spontaneously break down in the field, they need less effort. However, it's crucial to keep an eye on decomposition timetables in order to sustain soil health and crop cycles. After the season, organic mulches can be added to the soil to boost microbial activity and supply nutrients.

Environmental and Agronomic Advantages

Mulching improves crop productivity in a number of agronomic and environmental ways. Mulches enhance germination, promote early plant growth, and guarantee more consistent crop development by controlling soil temperature and retaining moisture, which results in increased

yields. In field tests, irrigation frequency was lowered by up to 40%, improving water-use efficiency. While reflective and colorful films can repel pests like aphids and thrips, mulches also reduce weeds, lessening competition and lowering the need for pesticides. By boosting microbial activity and encouraging nutrient cycling, organic mulches help create healthier soils. Hydrogels conserve water, promoting resilient and sustainable farming systems, while biodegradable mulches aid in lowering plastic pollution.

Economic Implications

By lowering irrigation, fertilizer, and pesticide costs, smart mulches can greatly increase agricultural profitability. Biodegradable or reflective mulches may initially cost more than conventional choices, but within a single season, the benefits from less work, less input consumption, and better water efficiency can make up for the investment. Strategic use of these mulches can increase cost-benefit ratios by 1.2–1.5 times, according to field studies in vegetable growing, making them a financially feasible choice for farmers while simultaneously promoting sustainable crop production.

Challenges and Limitations

Despite their advantages, smart mulches have a number of drawbacks that may prevent their widespread use. Small-scale farmers may be deterred by the greater initial cost of biodegradable or reflective materials as compared to traditional mulches. The performance and timing of nutrient release of biodegradable mulches can be impacted by a variety of factors, including crop rotation, soil type, and climate. In some areas, availability is frequently restricted, necessitating reliance on dependable providers. Furthermore, in order to guarantee correct installation, upkeep, and integration with irrigation and crop management techniques, farmers must be informed of and trained in the usage of smart mulches.

Future Prospects

Multifunctional designs that concurrently offer insect repellency, controlled nutrient release, and soil temperature and moisture regulation are the key to the future of smart mulches. Precision irrigation systems and soil sensors are examples of digital agricultural technology that may be integrated to maximize resource efficiency and performance. Global usage is anticipated to increase, especially for high-value crops and in areas with water constraint or extremely high or low temperatures. To ensure that smart mulches contribute sustainably to resilient and climate-adaptive agriculture, more study is required to assess long-term impacts on soil biology, decomposition dynamics, and overall environmental impact.

Conclusion

In order to control soil temperature and moisture, encourage healthy crop growth, and advance sustainable, climate-resilient agriculture, smart mulches are an efficient and scientifically proven method. Water conservation, increased yields, less insect pressure, weed suppression, and better soil health are just a few of the advantages they provide. Mulch must be carefully chosen, installed correctly, and integrated with irrigation and nutrient management techniques in order to reach its maximum potential. Smart mulches offer a workable solution to improve the productivity, efficiency, and environmental sustainability of contemporary farming systems when applied strategically.

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REDUCING CHEMICAL DEPENDENCY THROUGH BIOLOGICAL PRACTICES: A SUSTAINABLE PATHWAY FOR MODERN AGRICULTURE

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Abstract

Over the past few decades, agricultural productivity has increased dramatically due to an over-reliance on chemical pesticides and fertilizers, but this has also led to major problems like declining soil health, pollution of the environment, rising input costs, and diminished ecosystem resilience. Biological methods that make use of natural processes and helpful microorganisms are becoming more popular as sustainable substitutes for overuse of chemicals in response to these worries. These methods preserve agricultural output while lowering environmental hazards by increasing nutrient availability, suppressing pests and diseases, and boosting soil biological activity. The scientific argument for biological techniques, their underlying processes, key biological inputs and practices, field-level applications, and their contribution to long-term sustainability are all examined in this article. The focus is on how biological activities improve soil health, lower carbon footprints, and promote stable agro-ecosystems to support climate-resilient agriculture.

Keywords: Biological practices, reduced chemical inputs, soil health, biofertilizers, biopesticides, sustainable agriculture, climate-resilient farming

Introduction

For several decades, chemical inputs have formed the backbone of modern agricultural production. Synthetic insecticides and fertilizers were widely and even indiscriminately used due to their quick and obvious productivity benefits. However, the drawbacks of this input-intensive strategy have grown more noticeable over time. Long-term farm profitability and environmental sustainability are ultimately at risk due to the depletion of soil organic matter, nutrient imbalances, pest and disease resistance, contamination of soil and water resources, and a steady increase in production costs caused by prolonged and excessive use of chemicals.

Farmers and governments throughout the world are currently faced with a crucial question: how long can agricultural output be maintained only by increasing chemical inputs? A more sustainable and balanced course is offered by biological methods. These methods concentrate on progressively lowering reliance by reviving natural soil processes, boosting beneficial microbial activity, and bolstering ecosystem services rather than promoting the sudden removal of chemical inputs. Biological techniques offer steady yields while fostering soil health, environmental preservation, and climate variability resistance by cooperating with nature.

Understanding Chemical Dependency in Agriculture

When crop production depends more and more on larger dosages of synthetic fertilizers, insecticides, and growth regulators to maintain output levels, chemical reliance occurs in

agriculture. Continuous chemical application interrupts natural nutrient cycle mechanisms, lowers populations of helpful microbes, and progressively decreases soil biological activity. As a result, crops become more reliant on outside inputs for regular growth and production and become less effective at absorbing nutrients.

Biological Practices Concept

Agricultural methods that assist crop development, nutrition, and protection by utilizing live creatures or biological processes are referred to as biological practices. Instead of working against nature, these methods cooperate with it. Biological inputs boost plant defense systems, improve nutrient cycling, and promote soil life rather than using chemicals to force responses. Crop diversification, soil biological management, organic amendments, biofertilizers, and biopesticides are important biological techniques.

Role of Soil Biology in Reducing Chemical Inputs

Instead of being an inert growth medium, soil is a living habitat. It is home to a wide variety of microorganisms that are essential to preserving soil fertility, including bacteria, fungus, actinomycetes, protozoa, and algae. These organisms fix atmospheric nitrogen, break down organic wastes, release nutrients trapped in soil minerals, and enhance soil structure by creating stable aggregates. Repeated applications of synthetic fertilizers are less necessary when soil biological activity is maintained because nutrients become naturally accessible to crops in a balanced and effective way.

Additionally, stronger root systems, greater water retention, and increased stress tolerance are all supported by biologically active soils. Rebuilding and maintaining this biological system is made possible by management techniques including adding organic matter, reducing excessive tillage, holding onto agricultural leftovers, and introducing beneficial bacteria. Over time, crops are able to sustain yield with less chemical inputs as soil life recovers, nutrient use efficiency rises, and soil health improves.

Biological Substitutes for Chemical Fertilizers

Nutrient availability in the root zone is improved by biofertilizers such nitrogen-fixing bacteria, phosphorus-solubilizing microorganisms, potassium-mobilizing bacteria, and mycorrhizal fungi. These inputs, in contrast to chemical fertilizers, enhance nutrient efficiency as opposed to merely boosting nutrient availability. In many cropping systems, using biofertilizers in conjunction with lower dosages of chemical fertilizers has consistently been proven to sustain yields while reducing fertilizer usage by 20–50%.

Biological Approaches to Disease and Pest Management

In order to keep pest populations below harmful levels, biological pest and disease control depends on natural processes and beneficial species. With little danger to beneficial insects, non-target creatures, or the environment, biopesticides made from bacteria, fungus, viruses, and plant-based extracts provide tailored treatment of certain pests and diseases. These biological compounds, in contrast to broad-spectrum chemical pesticides, aid in maintaining the agricultural system's ecological equilibrium. Biological control mechanisms are reinforced by cultural and ecological behaviors. Crop rotation breaks the life cycles of pests and diseases, habitat management promotes the presence of natural enemies like parasitoids and carnivores, and beneficial insect conservation improves the natural control of pest populations. When combined, these strategies lessen the frequency and severity of pest outbreaks, lessen the need for chemical pesticides, and support more resilient and stable agro-ecosystems.

Biological Practices at the Crop and Farm Level

In addition to inputs, other agronomic techniques greatly lessen reliance on chemicals:

- Intercropping and crop rotation disrupt the cycles of pests and diseases.
- Green manures and cover crops naturally increase soil fertility.
- Using resistant cultivars lessens reliance on pesticides
- Soil health is improved via on-farm composting and residue recycling.

These methods provide steady, long-term advantages but operate slowly.

Field Experiences and Observations

Field observations from many agroecological regions demonstrate that farms implementing biological techniques progressively create soils that are healthier and more functioning. Soil structure, root penetration, moisture retention, and general crop uniformity all frequently show improvements. Farmers sometimes observe noticeable increases in crop vigor within one to two seasons, even though the first shift away from chemical-intensive management necessitates careful observation and balanced input usage. Many farmers report decreased fertilizer and pesticide expenditures after two to three cropping cycles, which lowers production costs and boosts profitability. Better production stability under stressful circumstances like drought, nutrient shortages, or mild insect impact is another recurring finding. Biologically managed systems are valuable in creating resilient and sustainable agricultural systems because they often protect crops from such pressures more successfully.

Economic and Environmental Implications

Reducing chemical reliance in agriculture minimizes crop losses due to chemical damage or imbalance, reduces labor and application costs, and lowers fertilizer and pesticide expenditures, all of which have a substantial positive economic and environmental impact. Over time, biologically managed systems increase agricultural profitability by increasing input-use efficiency. Reducing chemical usage protects groundwater quality and lowers chemical residues in food items by limiting nutrient leaching and pesticide runoff. Furthermore, biological methods assist climate-smart agricultural goals and sustainable intensification while maintaining long-term soil health and ecosystem stability by reducing greenhouse gas emissions associated with the manufacturing and overuse of synthetic fertilizers.

Challenges in Adoption

Adoption of biological methods is frequently hampered by issues including delayed observable responses than chemical inputs, inconsistent biological product quality and efficacy, poor farmer knowledge, and insufficient professional advice, despite their shown advantages. Farmers may be reluctant to use these methods at first because they are used to the rapid and predictable outcomes of synthetic herbicides and fertilizers. Effective extension services, stringent biological input quality regulations, ongoing farmer training, and the creation of crop-specific, location-specific suggestions to boost confidence and guarantee steady performance in the field are all necessary to overcome these limitations.

Future Outlook

The dependability of biological inputs is increasing due to developments in microbial technology, formulation science, and precision application. It is anticipated that further reducing chemical reliance without compromising production would be possible through the integration of biological techniques with digital technologies, soil health monitoring, and site-specific management.

Conclusion

Restoring equilibrium in agricultural systems is the goal of reducing chemical reliance using biological methods rather than completely doing away with chemicals. Biological methods provide a sustainable route for resilient and lucrative agriculture by boosting natural insect control, strengthening soil biology, and increasing nutrient efficiency. The secret to long-term success is a methodical, coordinated strategy.

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BEHIND EVERY NEW VARIETY: THE LONG JOURNEY OF CROP BREEDING

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Abstract

Every improved crop variety grown today is the result of years—often decades—of careful scientific effort. From selecting parents and making crosses to evaluating thousands of plants across seasons and locations, crop breeding is a long, patient journey. This article takes readers behind the scenes of plant breeding to show how new varieties are developed, tested, and finally delivered to farmers. It highlights the dedication, science, and fieldwork involved in transforming tiny seeds into climate-resilient, high-yielding crops that support global food security.

Keywords: Crop breeding; Plant breeding process; Variety development; Germplasm; Selection; Field evaluation; Climate-resilient crops; Food security.

Introduction

When a farmer opens a packet of seeds, it may seem like a simple beginning—a handful of small grains ready to be placed into the soil. Yet behind each seed lies a long and remarkable scientific journey, often stretching across ten or even fifteen years. Every new variety carries within it countless hours of careful planning, patient observation, repeated trials, unexpected failures, and hard-earned successes. What finally reaches the farmer is not just a seed, but the distilled result of generations of crossing, selection, testing, and refinement.

Crop breeding is never a one-season task. It is a slow, deliberate, and highly skilled process of improving plants to meet the constantly changing needs of agriculture. Breeders work to combine higher yield with better quality, stronger resistance with wider adaptability, and productivity with sustainability. Thousands of experimental lines are grown, observed, and rejected so that a few superior ones may move forward. Each step—crossing parents, selecting promising offspring, evaluating performance across locations, and confirming stability—demands time, precision, and deep biological understanding.

Today, this journey has become even more challenging and more important. As climate change intensifies, soils degrade, and water becomes scarcer, breeders are under increasing pressure to develop crops that can yield more food while using fewer resources and surviving harsher environments. At the same time, growing populations and changing diets demand crops that are not only productive, but also nutritious, safe, and suited to diverse farming systems.

Understanding the journey of crop breeding allows us to appreciate the unseen work that quietly shapes modern agriculture. It reveals that every successful harvest begins long before sowing—in research fields, greenhouses, and laboratories where scientists patiently build the crops of the future, one generation at a time.

Choosing the Right Parents

The journey of crop breeding begins with diversity. Long before any crossing is done, breeders explore vast germplasm collections, traditional farmer-saved varieties, and even wild relatives of crops to uncover valuable traits that modern agriculture needs. Within this genetic diversity lie natural solutions to many of today's challenges—genes for drought and heat tolerance, resistance to insects and diseases, early maturity, improved nutrient content, and adaptability to poor soils. This search is both scientific and strategic. Breeders carefully study plant characteristics, stress responses, and performance across environments to identify parent lines that possess complementary strengths. Some may yield well, others may survive harsh climates, and still others may carry resistance to devastating diseases. The goal is to assemble the best possible genetic foundation for the next generation. Just like building a strong family, selecting the right parents determines the potential of all future offspring. The quality, resilience, and productivity of tomorrow's crop varieties are rooted in these early choices. A thoughtful selection at this stage can mean the difference between a crop that merely survives and one that thrives in farmers' fields.

Making the Cross: Creating New Life

Once promising parents are identified, breeders carefully cross them by hand. This is a precise and deliberate process, where pollen from one selected plant is transferred to the flower of another under controlled conditions. Though the act itself may take only moments, it represents the merging of two carefully chosen genetic histories. The result is a small number of hybrid seeds, each carrying a completely new and unique genetic combination. Within these tiny seeds lies enormous possibility. Every one contains a different mix of traits from its parents—some favorable, some undesirable, and many unpredictable. In just a few grains, millions of genetic combinations are created, offering breeders a vast living library from which to select. At this stage, breeders are not creating a finished variety; they are opening the door to diversity.

These hybrid seeds mark the true beginning of the breeding journey. From here onward, the task is selection—growing large populations, observing differences, and patiently identifying the rare individuals that bring together the right balance of yield, resilience, quality, and adaptability. What follows is not a single experiment, but a long process of discovery guided by careful measurement, experience, and scientific insight.

Selection Across Generations

The next several years are devoted to growing, observing, and selecting plants across multiple seasons. Thousands—often tens of thousands—of offspring are planted in research fields and greenhouses. At first glance, many may look similar, but as they grow, their differences begin to appear. Some grow faster, some resist disease, some wilt under stress, and others thrive. With each generation, the population becomes a living experiment.

Breeders carefully evaluate every generation, recording both visible traits and hidden physiological strengths. They look not only at how much a plant produces, but also how it survives challenges.

Observations focus on:

- Yield potential – the plant's ability to produce stable and abundant harvests
- Stress tolerance – performance under drought, heat, or poor soil conditions
- Disease and pest resistance – natural protection against major biological threats
- Plant type and maturity – height, architecture, lodging resistance, and crop duration
- Grain or fruit quality – size, shape, nutrition, taste, and processing value

At each stage, difficult decisions are made. The majority of plants are discarded, even if they perform well in some traits, because only those with the best overall balance are advanced. Weak, unstable, or poorly adapted plants are systematically removed. Promising individuals are selected, replanted, and tested again.

With every generation, the population narrows, but its quality improves. What began as a sea of diversity gradually becomes a refined group of elite lines. This slow, disciplined process of selection is the heart of plant breeding, where patience and precision transform genetic possibility into agricultural reality.

Field Testing: From Plot to Farmer

Once promising lines emerge from early selection, the real test begins in farmers' conditions. These advanced breeding lines are evaluated across multiple seasons and diverse locations, representing different soil types, rainfall patterns, temperature regimes, and farming practices. What performs well in one experimental plot may fail elsewhere, so this stage is designed to answer a critical question: Will this crop perform reliably in the real world? In these multi-location and multi-year trials, breeders closely monitor yield stability, stress tolerance, disease reactions, maturity behavior, and quality traits. Crops are grown under both optimal and stress conditions to understand how they respond to drought, heat, flooding, or nutrient limitations. This helps identify varieties that are not just high-yielding, but also dependable. This stage often takes many years because true success in agriculture is not measured by a single good season. A new variety must demonstrate consistency, adaptability, and farmer suitability over time. It must fit local cropping systems, respond well to farmer management, and meet market and consumer expectations. Only after a line repeatedly proves its performance across environments does it move closer to release. By the time a new variety reaches farmers, it has already faced countless field challenges—ensuring that what is finally delivered is not an experiment, but a trustworthy tool for production.

Release, Seed Multiplication, and Farmer Adoption

Only after years of rigorous, multi-season, and multi-location testing does a breeding line finally earn the status of a named variety. At this point, it is no longer just an experimental line, but a potential contributor to farmers' livelihoods. The selected variety then enters the stage of large-scale multiplication, quality control, and certification to ensure that the seed farmers receive is genetically pure, healthy, and reliable. Public and private seed systems work to increase seed quantities so that what was once a handful of grains can reach thousands of fields.

Yet the journey does not end at release. Even after a variety is officially recommended, researchers and extension workers continue to monitor its performance in farmers' fields. They observe how it responds under real management practices, diverse soils, and unpredictable weather. Farmer feedback becomes a vital part of this phase, guiding further improvement and helping identify strengths, limitations, and new breeding goals. Ultimately, a variety's real success is not measured in research plots or trial reports, but in farmers' harvests. It is seen in stable yields under stress, in reduced crop losses, in better grain quality, and in the confidence of farmers who choose to plant it season after season. When a seed performs reliably in the hands of farmers, the long scientific journey behind it finds its true purpose.

Future of Crop Breeding

Modern breeding is now supported by a powerful set of tools that are transforming how new crop varieties are developed. Technologies such as molecular markers and genomics allow breeders to

look directly into a plant's DNA and identify individuals carrying desirable genes long before those traits are visible in the field. Speed breeding techniques enable multiple generations to be grown each year under controlled conditions, dramatically shortening the time needed to fix useful traits. Advances in phenomics, supported by artificial intelligence, imaging systems, sensors, and drones, make it possible to measure plant growth, stress responses, and productivity with unprecedented accuracy and scale. Gene editing and precision breeding further allow scientists to make targeted improvements, accelerating the development of crops with enhanced resilience, nutrition, and efficiency.

These technologies are accelerating the breeding journey, improving precision, and reducing uncertainty. However, they do not replace the breeder's eye, field experience, or deep understanding of crops and farming systems. A machine may measure traits, but it is the breeder who interprets them. A gene may be edited, but it is the field that decides its value. The success of modern breeding still depends on careful observation, farmer feedback, and long-term field evaluation. Technology enhances the process—but it is human insight, patience, and connection to the land that ultimately transform scientific potential into seeds farmers can trust.

Conclusion

Behind every successful crop variety lies a long journey of vision, science, and perseverance. Crop breeding is a quiet but powerful force that shapes food security, strengthens climate resilience, and supports rural livelihoods across the world. Long before a seed reaches a farmer's hand, it has passed through years of careful planning, countless field trials, failed attempts, and patient selection.

Every time a farmer plants an improved seed, they are planting much more than a crop. They are planting years of research, thousands of observations, and the combined effort of breeders, technicians, and farmers who worked across seasons and landscapes. They are also planting hope—the hope of a better harvest, a more secure income, and a future where agriculture continues to feed both people and the planet.

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REBUILDING RESILIENCE IN INDIAN AGRICULTURE: INTEGRATING FARMING SYSTEMS AND NUTRIENT MANAGEMENT UNDER CLIMATE STRESS

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Abstract

Climate change poses significant risks to agricultural productivity, resource sustainability, and farm incomes in India. Integrated Farming Systems (IFS) have gained attention as a climate-resilient agricultural strategy that combines cropping, livestock, fisheries, agroforestry, and allied enterprises to enhance resource use efficiency, diversify income, and improve soil fertility and nutrient cycling. Central to IFS is Integrated Nutrient Management (INM), which optimises the use of organic and inorganic fertilisers, improves nutrient-use efficiency (NUE), and supports long-term soil health. This paper reviews the role of IFS in climate resilience, emphasising nutrient management, fertiliser response, and sustainability. It synthesises empirical evidence from peer-reviewed studies and discusses policy and practice implications for India's smallholder-dominated agricultural sector. Findings underscore that IFS with strong INM components can enhance productivity, reduce input dependence, lower greenhouse gas emissions, and strengthen livelihoods under climate variability.

Introduction

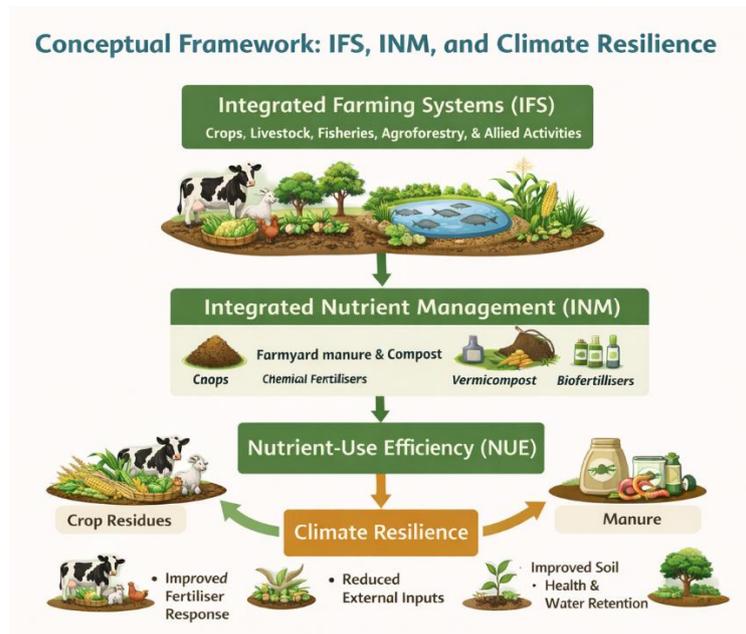
India's agriculture faces mounting challenges due to increasing climate variability, including erratic rainfall, temperature extremes, droughts, and floods. Such climatic shocks adversely affect crop growth, yield stability, and input efficiency, while also destabilising farmer incomes and degrading soil and water resources (Sahoo *et al.*, 2024; Singh *et al.*, 2020). Traditional monocropping systems, which often rely heavily on chemical fertilisers and standardised farming practices, demonstrate limited resilience under these variable conditions. Excessive or imbalanced fertiliser use in such systems not only reduces nutrient-use efficiency (NUE) but also contributes to soil degradation, greenhouse gas emissions, and declining long-term productivity. This scenario underscores the urgent need for holistic agricultural systems that simultaneously enhance nutrient efficiency, maintain soil health, and build climate resilience while supporting farmer livelihoods.

Integrated Farming Systems (IFS) have emerged as a practical and scalable solution to these challenges. IFS combine multiple enterprises - crops, livestock, poultry, fisheries, agroforestry, and allied activities within a single farm unit to optimise resource use, improve nutrient cycling, and diversify income sources. By converting farm outputs from one enterprise into inputs for another, such as using crop residues and livestock manure as organic fertilisers, IFS reduce dependence on synthetic fertilisers, improve fertiliser response, and increase soil organic carbon. These nutrient management synergies are central to Integrated Nutrient Management (INM) strategies, which aim to optimise the balance of organic and inorganic inputs to enhance crop productivity and environmental sustainability. The relevance of IFS is particularly pronounced in India, where small and marginal farmers constitute the majority of agricultural households and are most vulnerable to climate shocks. By integrating diversification, nutrient recycling, and risk management, IFS provide

a pathway to resilient, profitable, and sustainable agriculture. This paper examines how IFS, coupled with robust fertiliser and nutrient management practices, can strengthen climate resilience, improve NUE, and support sustainable intensification, drawing on evidence from peer-reviewed literature across diverse Indian agro-ecological regions.

Conceptual Framework: IFS, INM, and Climate Resilience

Integrated Farming Systems (IFS) are defined as the systematic combination of multiple, complementary agricultural enterprises within a single farm to generate mutually supportive interactions and optimise resource use (Pradhan *et al.*, 2025). Unlike conventional monocropping, IFS emphasise diversification, nutrient recycling, and risk spreading, creating resilient systems capable of maintaining productivity under variable climatic conditions (Singh *et al.*, 2025). By integrating crops, livestock, fisheries, agroforestry, and allied activities, IFS transform farm outputs into closed-loop nutrient cycles: crop residues feed livestock, animal dung and urine are recycled as compost, vermicompost, or biogas slurry, and green manures enhance soil organic matter. This synergy ensures that nutrients remain on the farm, improving fertiliser efficiency and reducing dependence on external chemical inputs. A central component of IFS is Integrated Nutrient Management (INM), which strategically combines organic and inorganic nutrient sources to optimise crop uptake and improve nutrient-use efficiency (NUE). INM leverages the complementary benefits of farmyard manure, compost, biofertilisers, and chemical fertilisers to synchronise nutrient supply with crop demand, reduce losses through leaching or volatilisation, and maintain long-term soil fertility. In doing so, INM supports both economic and environmental sustainability by lowering input costs, enhancing fertiliser response, and mitigating greenhouse gas emissions. From a climate-resilience perspective, IFS provide multiple buffering mechanisms. Diversified enterprises reduce the risk of total crop failure due to drought, floods, or pest outbreaks, while nutrient-rich soils with higher organic matter improve water retention, microbial activity, and plant stress tolerance. Agroforestry components moderate microclimates, reducing temperature extremes and wind stress. Together, IFS and INM form a holistic framework where nutrient management, productivity, and climate adaptation converge, offering a scalable pathway for sustainable, resilient, and profitable Indian agriculture.



IFS Components and Climate Adaptation Pathways

Integrated Farming Systems (IFS) enhance climate adaptation by combining complementary farm enterprises that improve resilience to climatic variability. Through diversification, efficient nutrient recycling, and integrated water management, IFS reduce vulnerability to droughts, floods, and temperature extremes. These interconnected components strengthen system stability, sustain productivity, and support adaptive capacity under changing climate conditions.

Diversification and Risk Reduction

Diversification is a foundational principle of Integrated Farming Systems (IFS) and a critical mechanism for climate adaptation in Indian agriculture. By integrating crops, livestock, fisheries, and allied enterprises, IFS distribute production and income risks across multiple components. Climate-induced stresses such as droughts, floods, heat waves, or pest outbreaks rarely affect all enterprises simultaneously. As a result, diversified farms are inherently more resilient than monocropping systems, which are highly vulnerable to single climatic shocks. For example, while crop yields may decline during drought years, livestock or fisheries may continue to generate income, thereby stabilising farm livelihoods.

Empirical evidence from rainfed and semi-arid regions demonstrates that integrated crop–livestock systems significantly reduce inter-annual income variability and improve overall farm stability. Studies by Chary *et al.*, (2022) and Pradhan *et al.*, (2025) show that diversified systems produce higher system-equivalent yields and offer more consistent returns than sole-crop systems. Beyond economic benefits, diversification enhances adaptive capacity by allowing farmers to flexibly reallocate resources—such as labour, residues, and water—among enterprises in response to changing climatic conditions. Thus, diversification under IFS functions as both an economic safety net and a strategic adaptation pathway for climate-resilient agriculture.

Nutrient Recycling and Soil Fertility

Integrated Farming Systems enhance climate resilience by promoting efficient nutrient recycling within the farm ecosystem. Crop residues, straw, and processing by-products are used as livestock feed, while animal dung and urine are recycled as farmyard manure, compost, or biogas slurry. This closed-loop nutrient flow reduces reliance on external fertiliser inputs and minimises nutrient losses from the system. Recycling organic resources increases soil organic matter, which is a key determinant of soil health and climate adaptability. Improved soil organic matter enhances soil structure, aggregation, and porosity, leading to better water infiltration and retention. These properties enable soils to buffer against moisture stress during droughts and reduce runoff and erosion during high-intensity rainfall events. Empirical studies report higher soil organic carbon, microbial biomass, and enzymatic activity under integrated nutrient cycling compared to systems dependent solely on inorganic fertilisers. Research by Pradhan *et al.*, (2025) and Manjunath *et al.*, (2025) highlights that such improvements contribute to long-term soil fertility and sustained productivity. By strengthening soil resilience and nutrient availability, IFS-based nutrient recycling plays a central role in climate adaptation and sustainable intensification.

Water Management and Productivity

Water management is a critical adaptation pathway within IFS, particularly in drought-prone and rainfed regions. Rainwater harvesting structures such as farm ponds, check dams, and field bunds enhance water availability by capturing excess rainfall during the monsoon. Stored water provides supplementary irrigation during dry spells, reducing crop failure risks and stabilising yields. In IFS,

these structures also support allied enterprises such as fish culture, thereby increasing water productivity and diversifying income sources. The integration of water and nutrient management creates important synergies within IFS. Supplemental irrigation improves nutrient uptake efficiency by maintaining soil moisture at critical crop growth stages, while organic matter from integrated nutrient recycling enhances soil water-holding capacity. Studies indicate that such integrated approaches improve overall system efficiency and resilience under variable rainfall conditions. Evidence from Pradhan *et al.*, (2025) and Singh *et al.*, (2025) shows that farms adopting water-harvesting-based IFS exhibit higher system productivity and reduced vulnerability to climate-induced water stress. Thus, integrated water management strengthens both productivity and adaptive capacity in climate-sensitive agricultural systems.

Integrated Nutrient Management (INM): Enhancing Fertiliser Response and NUE4.1 Role of INM in IFS

Integrated Nutrient Management (INM) is a cornerstone of Integrated Farming Systems (IFS), as it enables efficient utilisation of diverse nutrient sources generated within the farm while maintaining optimal fertiliser use. By combining chemical fertilisers with organic manures, crop residues, green manures, and biofertilisers, INM improves synchrony between nutrient supply and crop demand. This is particularly critical in IFS, where livestock, crop, and allied enterprises generate recyclable organic resources that can partially substitute external fertiliser inputs. For smallholder farmers, INM reduces dependence on costly fertilisers, buffers against price volatility, and enhances system self-reliance. Empirical evidence from rice-based systems in India demonstrates that integrating farmyard manure or compost with recommended fertiliser doses significantly improves soil organic carbon, microbial biomass, and enzymatic activity compared to sole chemical fertiliser use. Improved soil biological activity enhances nutrient mineralisation and availability, resulting in better crop growth and yield response. INM also improves soil physical properties such as aggregation, porosity, and water-holding capacity, which are essential for sustaining productivity under climatic stress. Within IFS, INM strengthens internal nutrient cycling by converting animal waste, crop residues, and by-products into valuable nutrient inputs. This recycling minimises nutrient losses through runoff, leaching, and volatilisation, while enhancing long-term soil fertility. By maintaining soil health and reducing environmental losses, INM ensures that IFS remain productive, economically viable, and ecologically sustainable over time.

Empirical Evidence on INM and Crop Performance

A substantial body of empirical research across diverse agro-ecological regions of India highlights the positive impact of INM on crop performance and soil fertility. Studies in paddy systems of the Northeast Himalayan region show that combining organic manures and biofertilisers with inorganic fertilisers leads to significant improvements in plant height, tiller number, grain yield, and nutrient uptake. Enhanced soil nitrogen, phosphorus, and potassium availability under INM reflects improved nutrient retention and reduced fixation losses, particularly in acidic and high-rainfall environments. Similar benefits have been reported in upland paddy, cereals, pulses, and oilseed systems, where INM not only increased yields but also improved energy-use efficiency and benefit-cost ratios. Integrated nutrient strategies reduce the energy intensity associated with fertiliser production and application, thereby lowering the overall carbon footprint of crop production. The synergistic effects of organic and inorganic inputs ensure more stable yields across seasons, particularly under variable rainfall and temperature regimes. Beyond yield enhancement, INM contributes to long-term sustainability by preventing nutrient mining and soil degradation.

Continuous reliance on chemical fertilisers alone has been associated with declining fertiliser response ratios, whereas INM restores soil productivity by replenishing both macro- and micronutrients. These findings underscore the role of INM as a scientifically validated and economically sound strategy for improving crop performance within IFS frameworks.

Nutrient Use Efficiency Under IFS

Nutrient use efficiency (NUE) is a critical indicator of both economic performance and environmental sustainability in agriculture. Under IFS, NUE is significantly enhanced through the synergistic effects of organic inputs, biofertilisers, and diversified cropping patterns. Organic manures and composts improve nutrient retention in soil by increasing cation exchange capacity and reducing nutrient losses, while their slow-release characteristics ensure sustained nutrient availability throughout the crop growth cycle. Microbial bio-inputs further enhance NUE by solubilising phosphorus, fixing atmospheric nitrogen, and improving root nutrient uptake. These biological processes reduce the requirement for high chemical fertiliser doses, thereby lowering production costs and minimising environmental externalities such as nitrate leaching and nitrous oxide emissions. The inclusion of legumes within IFS adds an additional layer of efficiency through biological nitrogen fixation, improving nitrogen balance and reducing dependence on synthetic nitrogen fertilisers. Improved NUE under IFS translates into higher fertiliser response ratios and greater yield stability, particularly under stress-prone rainfed conditions. By optimising nutrient flows at the system level, INM ensures that applied nutrients are effectively converted into harvestable produce rather than lost to the environment. This makes INM a central mechanism through which IFS achieve productivity gains while simultaneously advancing climate mitigation, resource conservation, and long-term soil health.

Operationalising Nutrient Based Subsidy (NBS)–2024 for IFS

The infographic explains how the Nutrient Based Subsidy (NBS)–2024 can be effectively implemented through Integrated Farming Systems (IFS) to improve nutrient-use efficiency and build climate-resilient agriculture. It shows how policy support, soil-based recommendations, and farm-level practices can work together to make fertiliser use more balanced, efficient, and sustainable. NBS-2024 promotes balanced fertilisation by encouraging customised, fortified, and bio-fertilisers instead of excessive use of nitrogen. When combined with Soil Health Card recommendations, farmers can apply nutrients according to the actual needs of their soils and crops, reducing wastage and improving fertiliser response under changing weather conditions. The IFS approach integrates crop diversification, livestock, organic nutrient sources, and on-farm residue recycling. Organic inputs such as compost, biogas slurry, green manure, and livestock manure help recycle nutrients within the farm, improve soil organic matter, and enhance microbial activity. Crop diversification reduces production risk, improves nutrient cycling, and increases overall system stability. At the field level, the framework highlights three key practices: balanced fertilisation, use of bio/fortified fertilisers, and precision nutrient management. Together, these practices correct long-standing NPK imbalances, reduce nutrient losses, and increase nutrient-use efficiency. The combined impact is higher and more stable productivity, lower environmental pollution, and improved soil health. By linking NBS-2024 with IFS practices, the framework offers a practical pathway for farmers to achieve sustainable yields, reduced input costs, and climate-resilient farming systems, supporting long-term livelihoods and environmental protection.



Climate Mitigation and Environmental Benefits

Climate change mitigation in agriculture focuses on reducing greenhouse gas (GHG) emissions while enhancing the capacity of farming systems to sequester carbon and protect natural resources. Integrated Farming Systems (IFS) offer a strong mitigation pathway by combining diversified production components with efficient nutrient and biomass management, thereby lowering the environmental footprint of agriculture. A major mitigation benefit of IFS lies in enhanced carbon sequestration, particularly through improvements in soil organic carbon (SOC). The regular application of organic amendments such as compost, farmyard manure, biogas slurry, green manures, and recycled crop residues increases carbon inputs to soil. Diversified cropping, inclusion of legumes, and continuous ground cover further reduce carbon losses and promote stable carbon pools. Higher SOC not only mitigates atmospheric CO₂ but also improves soil structure, water-holding capacity, and nutrient retention, creating positive feedbacks for productivity and resilience.

IFS also contribute to mitigation by reducing dependence on energy-intensive chemical fertilisers. Partial substitution of synthetic fertilisers with organic and biological nutrient sources lowers emissions associated with fertiliser manufacture, transport, and application. Balanced nutrient management under IFS improves nutrient-use efficiency, thereby reducing nitrous oxide (N₂O) emissions arising from excessive or poorly timed nitrogen application. Improved recycling of on-farm biomass and animal waste further minimises nutrient losses and associated emissions. The inclusion of agroforestry and perennial components within IFS plays a critical role in moderating microclimates and sequestering carbon both above and below ground. Trees and shrubs act as long-term carbon sinks while reducing temperature extremes, wind speed, and evapotranspiration at the farm level. These microclimatic benefits help stabilise crop yields under heat and moisture stress while contributing to landscape-level climate regulation (turn1search8; Pradhan *et al.*, 2025). Beyond climate mitigation, IFS deliver broader environmental co-benefits, including reduced nutrient runoff, improved biodiversity, and lower soil degradation. Together, these outcomes align IFS with India's national climate commitments under the Paris Agreement, as well as emerging sustainability frameworks that emphasise low-emission, resource-efficient agricultural growth. By integrating mitigation directly into productive farming systems, IFS represent a practical and scalable approach to climate-smart and environmentally responsible agriculture.

Policy and Institutional Support for IFS and INM in India

Effective scaling of Integrated Farming Systems (IFS) and Integrated Nutrient Management (INM) in India depends not only on technological viability but also on enabling policy and institutional frameworks. Given the goals of productivity enhancement, climate resilience, and resource conservation, IFS–INM aligns well with several national agricultural and climate initiatives. Strategic convergence of policies, institutions, and extension mechanisms is therefore essential to translate scientific evidence into widespread farm-level adoption.

1. Alignment with Climate-Resilient Agriculture Programme

India's policy framework provides entry points for scaling IFS–INM through climate-focused initiatives. The National Initiative on Climate Resilient Agriculture (NICRA) emphasises soil health improvement, efficient resource use, and climate adaptation, offering a suitable platform for integrating diversified farming systems and nutrient recycling approaches.

2. Soil Health and Integrated Soil Fertility Policies

National soil health initiatives promote soil testing, balanced fertiliser application, and integrated soil fertility management. These policies support the combined use of mineral fertilisers, organic amendments, crop residues, and bio-inputs, which are core principles of INM and essential for sustaining productivity and resilience within IFS.

3. Fertiliser Policy and Nutrient-Use Efficiency

Existing fertiliser policies aimed at improving nutrient-use efficiency can be strengthened by explicitly linking them with INM and IFS. Encouraging site-specific and balanced nutrient application, along with recycling of on-farm organic resources, can reduce nutrient losses and environmental externalities.

4. Role of Extension Services and KVKs

Public extension systems and Krishi Vigyan Kendras (KVKs) are central to building farmer capacity in integrated nutrient management and multi-enterprise farming. Demonstrations, field schools, and adaptive trials can translate policy objectives into practical, location-specific solutions.

5. Farmer Producer Organisations (FPOs) as Institutional Platforms

FPOs can facilitate collective access to inputs, credit, mechanisation, and markets for diversified outputs such as milk, fish, horticulture, and organic inputs. They also provide effective platforms for training, aggregation, and value-chain development under IFS.

6. Need for Policy Convergence and Incentives

Scaling IFS–INM requires convergence across fertiliser, soil health, climate adaptation, and rural development schemes. Policy incentives that reward fertiliser efficiency, organic resource recycling, and diversified production—rather than single-crop yield maximisation—are critical for mainstreaming IFS as a sustainable agricultural strategy in India.

Challenges and Future Directions

While Integrated Farming Systems (IFS) combined with Integrated Nutrient Management (INM) offer a compelling pathway for sustainable and climate-resilient agriculture, their widespread adoption remains uneven. Multiple technical, economic, and institutional constraints limit effective implementation across diverse farming contexts in India. Addressing these challenges and identifying clear future research and policy directions are critical for scaling IFS–INM as a mainstream agricultural strategy.

Challenges

1. Knowledge and Skill Gaps

Adoption of IFS–INM is constrained by limited farmer awareness and technical capacity. Managing multiple enterprises and understanding nutrient cycling, recycling pathways, and system interactions require skills that are not adequately addressed through existing extension and training mechanisms.

2. High Initial Investment Requirements

Establishment of IFS components such as farm ponds, livestock housing, biogas units, composting structures, and manure management facilities involves significant upfront capital. Small and marginal farmers often lack access to affordable credit and are hesitant to invest due to delayed economic returns.

3. Market and Credit Constraints

Weak market linkages for diversified outputs (milk, fish, horticultural produce, organic inputs) reduce profitability. In addition, limited institutional credit, insurance coverage, and absence of assured price incentives restrict farmers' willingness to diversify beyond conventional monocropping systems.

4. Policy and Institutional Limitations

Current agricultural policies largely emphasize input subsidies and single-crop productivity, with limited recognition of ecosystem services such as nutrient recycling, soil carbon sequestration, and environmental benefits generated by IFS.

Future Directions

The future of climate-resilient Indian agriculture lies in advancing Integrated Farming Systems (IFS) and fertiliser nutrient management from concept-driven approaches to scalable, region-specific solutions. Greater emphasis is needed on precision nutrient management, digital decision-support tools, and participatory research that aligns scientific innovation with farmers' realities. Policy frameworks that incentivise nutrient-use efficiency, resource recycling, and ecosystem services will be central to mainstreaming IFS–INM as a cornerstone of sustainable agricultural transformation.

1. Region-Specific IFS Models

Research should focus on developing location-specific IFS–INM models tailored to agro-climatic conditions, resource availability, and socio-economic contexts to improve relevance and adoption.

2. Precision and Digital Nutrient Management

Integration of precision nutrient management tools, decision-support systems, and digital advisory services can help farmers optimize nutrient use, reduce losses, and manage system complexity.

3. Participatory Research and Capacity Building

Stronger farmer–scientist–extension linkages and participatory research approaches are essential for co-developing practical, scalable IFS solutions.

4. Economic and Policy Incentives

Policy mechanisms that reward fertiliser efficiency, resource conservation, and ecosystem services—such as carbon and nutrient credits, targeted subsidies, and convergence of schemes—can significantly accelerate adoption of IFS–INM systems.

Epilogue

As Indian agriculture navigates an era of intensifying climate uncertainty, the pathway forward lies not in isolated technological fixes but in systemic transformation. Integrated Farming Systems, strengthened by scientifically grounded fertiliser nutrient management, offer a paradigm that reconciles productivity with resilience, and short-term gains with long-term sustainability. By re-embedding nutrient flows within the farm ecosystem and diversifying livelihood sources, IFS redefines fertiliser use from an input-intensive practice to a resource-efficient, adaptive strategy.

The evidence presented in this paper underscores that climate resilience is not an external add-on but an emergent property of well-integrated systems—where soils function as living reservoirs, nutrients circulate efficiently, and enterprises mutually reinforce one another. Such systems are particularly relevant for India’s smallholder-dominated agriculture, where risk exposure is high and resource margins are narrow. IFS–INM thus represents both a scientific advancement and a socio-ecological response to climate stress.

Looking ahead, the challenge is to move from proof-of-concept to scale. This will require aligning fertiliser policy, climate missions, extension systems, and market incentives around system-level outcomes rather than single-input efficiencies. Investments in knowledge, institutions, and ecosystem-service valuation will determine whether IFS–INM remains a niche intervention or evolves into a cornerstone of India’s climate-resilient agricultural future.

In conclusion, scaling IFS combined with INM requires coordinated policy and institutional interventions that move beyond crop-centric productivity goals towards system-based resilience outcomes. Strengthening extension services, promoting region-specific IFS models, leveraging digital advisory tools, and incentivising fertiliser efficiency and ecosystem services are essential. IFS–INM represents a viable, science-backed framework for transforming Indian agriculture into a more resilient, resource-efficient, and sustainable system capable of meeting future food and environmental challenges.

Conclusion

Integrated Farming Systems, when coupled with robust Integrated Nutrient Management, offer a viable pathway to build climate-resilient agriculture in India. By enhancing nutrient recycling,

fertiliser response, soil health, and income diversification, IFS support sustainable intensification under changing climatic conditions. Evidence from peer-reviewed research underscores the benefits of INM on soil quality, nutrient efficiency, and crop productivity. Policy alignment with soil health initiatives, climate resilience programmes, and fertiliser sector reforms can accelerate adoption and scaling. Integrated approaches that combine organic and inorganic nutrient sources, leverage diversification, and improve resource use efficiency will be central to strengthening India's agricultural resilience, environmental sustainability, and farmer livelihoods.

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ADENIUM AS A HIGH VALUE ORNAMENTAL CROP

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Abstract

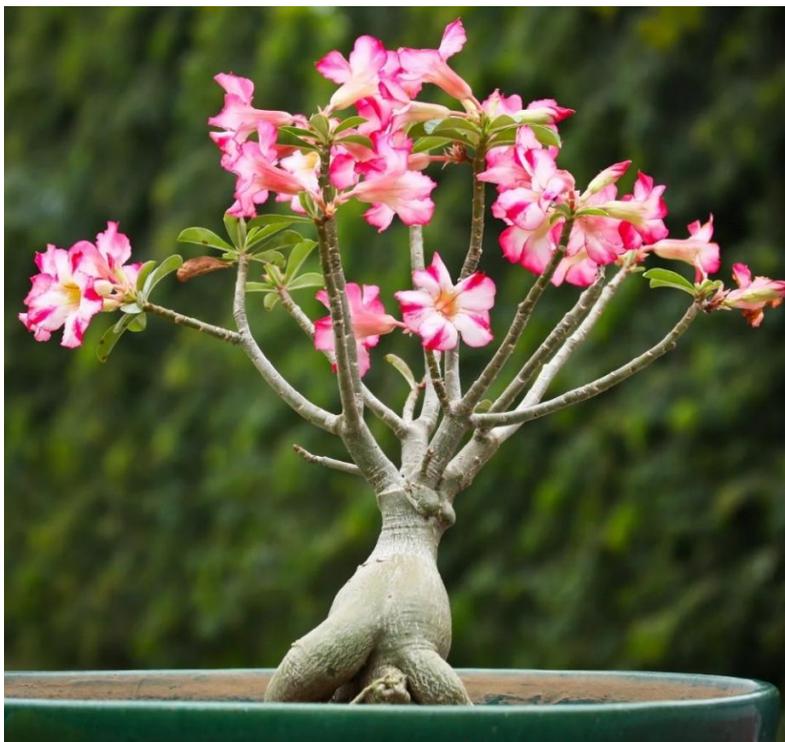
Adenium obesum (desert rose) is a highly valued ornamental succulent, prized for its striking caudex, vibrant flowers, and drought tolerance. Widely cultivated in temperate and tropical regions, it is suitable for container culture, bonsai, and xeriscaping. Propagation is achieved through seeds, grafting, and cuttings, with grafting preferred for uniformity and superior ornamental traits. Optimal cultivation involves well-drained media, proper irrigation, nutrient management, pruning, and periodic repotting to ensure healthy growth and flowering. The species is susceptible to pests such as mealybugs and spider mites, and fungal diseases, which can be managed through preventive and integrated practices. Commercialization of *Adenium* has expanded globally and in India, driven by its aesthetic appeal, adaptability, and growing urban gardening trends. With rising consumer interest, e-commerce availability, and opportunities in bonsai culture, *Adenium* presents significant prospects for domestic and international markets, making it a lucrative ornamental crop.

Introduction

Adenium obesum (Forssk.) Roem. & Schult., commonly known as the desert rose or impala lily, has emerged as a highly sought-after ornamental plant in global pot-plant culture. Its growing popularity can be attributed to its striking sculptural caudex, exceptional tolerance to drought, and its robust branching and profuse flowering habit (Singh *et al.*, 2023). Botanically, *Adenium* is a long-lived tropical succulent perennial, ideally suited for rooftop gardening, container culture, and xeriscaping systems. *Adeniums* belonging to the family Apocynaceae, *A. obesum* is native to arid and semi-arid regions of Africa and the Arabian Peninsula, extending from Senegal to Sudan and Kenya, and into Saudi Arabia, Oman, and Yemen. The genus name *Adenium* is derived from the Arabic word *oddaejn*, referencing its regional origin. The species is distinguished by its swollen, water-storing stem and roots, an adaptive feature that enables survival under extreme temperature fluctuations and prolonged moisture stress.

The ornamental value of *Adenium* is enhanced by its vivid floral display, ranging from deep pink and crimson to white, coupled with its unique trunk architecture. These attributes make it an outstanding specimen for both outdoor landscapes and indoor décor. Its adaptability to diverse climatic conditions and minimal maintenance requirements have further contributed to its acceptance among hobbyists and professional growers alike.

In recent years, the increasing trend toward compact urban living has amplified the demand for resilient ornamental plants capable of thriving in limited spaces without compromising visual appeal. Concurrently, the renewed interest in bonsai and miniature tree cultivation has elevated *Adenium's* status, as its natural form aligns seamlessly with this art form.



Adenium plant

Within the Indian horticultural market, Adenium has witnessed a marked rise in popularity due to its climatic compatibility, affordability, and high aesthetic value. The plant holds considerable promise for commercial cultivation, presenting opportunities for growers and entrepreneurs to capitalize on expanding domestic demand as well as emerging international markets. Given the sustained growth of home gardening and ornamental plant industries, Adenium is poised to remain a prominent and profitable component of the floriculture sector.

Cultivation and uses

Adenium obesum is widely cultivated as a houseplant in both temperate and tropical regions, owing to its adaptability and ornamental value. Over the years, extensive hybridization efforts have resulted in the development of numerous cultivars exhibiting diverse floral colours, forms, and growth habits. The species is particularly valued for its vibrant blossoms and its distinctive, swollen caudex, which contributes significantly to its sculptural appeal. When maintained under appropriate conditions, Adenium can thrive for many years in container culture and is especially favoured for bonsai and miniature landscape designs. The plant produces paired, follicular fruits that split open upon maturity to release seeds. These seeds are characteristically equipped with a double pappus, tufts of fine hairs at both ends, which facilitates effective wind dispersal in natural habitats. However, plants raised from seed exhibit considerable genetic variability and do not remain true to type, limiting their suitability for maintaining elite ornamental traits. To preserve desirable characteristics such as flower colour, form, and growth architecture, vegetative propagation through grafting is commonly employed in commercial production. Grafting ensures genetic uniformity and enables the rapid multiplication of superior cultivars. While clonal propagation can also be achieved through stem cuttings, plants produced by this method generally exhibit slower and less pronounced caudex development compared to seed-grown individuals, thereby reducing their ornamental value in certain applications.

Propagation

Adenium obesum can be propagated through both sexual and vegetative methods. Seed propagation is widely practiced as it promotes strong root systems and the development of a characteristic swollen caudex; however, seedlings show considerable genetic variation and may not retain the traits of the parent plant. To ensure uniformity in flower colour, form, and growth habit, vegetative propagation—particularly grafting—is preferred in commercial production. Stem cuttings are also used for clonal multiplication, but plants raised from cuttings usually exhibit slower and less pronounced caudex formation, which may limit their ornamental value.

Growing media

For optimal growth, *Adenium* requires a well-aerated growing medium that also retains adequate moisture without becoming waterlogged. Selection of the growing media should be closely aligned with the irrigation schedule, or alternatively, watering practices should be adjusted to suit the chosen substrate. For example, media with low water-holding capacity are more appropriate for production systems that involve frequent watering, as they help prevent excess moisture and root-related disorders.

Containers

Plastic containers perform equally well, and in many cases better, than porous clay pots when a well-aerated growing medium is used and irrigation is properly regulated. Plant performance is influenced more by container shape than by container material. Deeper pots are preferred during the early stages of growth as they encourage better root development, whereas shallow pots or bowls are more suitable for mature plants and for display purposes. Adequate drainage is essential; containers should have sufficient drainage holes, as prolonged water stagnation can be fatal to *Adenium*.

Nutrition

Under favourable growing conditions, *Adenium* exhibits rapid growth and consequently has a high demand for nitrogen and other essential nutrients. However, excessively fast growth often results in weak, unattractive tissues that are highly susceptible to rot. Nutrient application should therefore be managed carefully—supplemental feeding is recommended during active growth phases, while a low and steady basal nutrient supply should be maintained during periods of slower growth. Seed-producing mother plants, in particular, require enhanced levels of specific nutrients to ensure optimal seed quality. The use of a balanced, full-spectrum liquid fertiliser containing all essential macronutrients (nitrogen, phosphorus, potassium, calcium, magnesium, and sulphur) along with micronutrients (iron, manganese, copper, zinc, boron, and molybdenum) is recommended for sustained plant health and productivity.

Pruning

Pruning is a highly effective cultural practice for promoting flowering in grafted *Adenium* plants, as floral initiation is closely associated with the emergence of new shoots, particularly under cool conditions and shorter day lengths. This practice is especially beneficial for plants grown under suboptimal conditions that limit vegetative growth. In contrast, under favourable environments, *Adeniums* tend to produce elongated stems with reduced flowering unless properly managed.



Pruning in *Adenium*

Regular pinching of seedlings encourages early branching and results in a compact, well-structured plant. For established plants that have attained sufficient height, annual pruning or at minimum once every two years, is recommended. During pruning, thinning can be carried out to remove weak, damaged, or inward-growing shoots, thereby improving plant architecture and air circulation. This practice also aids in reducing infestations of common pests such as mealybugs and spider mites, which typically congregate near actively growing shoot tips.

Timely pruning during active growth is essential; otherwise, apical dominance may result in the emergence of only a single new shoot. Over time, *Adeniums* develop an extensive root system with thickened secondary roots. During repotting, these roots are often trimmed near their junction with the caudex to facilitate placement in new containers and to ensure adequate space for fresh growing media. Additionally, rejuvenation pruning of older plants with elongated, leafless stems during spring effectively revitalizes growth, stimulates branching, and promotes subsequent flowering.

Repotting

Regular repotting, either once or twice a year, is beneficial for maintaining healthy growth in *Adenium* plants. During repotting, the old growing medium may be completely removed—particularly if it has degraded or become excessively water-retentive—or partially retained, with the remaining space in the container filled using fresh medium. The most suitable time for repotting is spring, when new growth is initiating, as rapid root regeneration during this period supports vigorous shoot development.

In some cases, the root system may become excessively dense and difficult to accommodate in a new container. Under such circumstances, selective root pruning can be carried out without adversely affecting plant health, especially when secondary roots possess narrow necks near the main caudex. Repotting also provides an opportunity to thin overcrowded plants and trim stems, thereby improving plant structure and encouraging balanced growth.

Flowering

Adenium produces terminal inflorescences that emerge from the apical region of the branches. These inflorescences are typically corymbose and bear a variable number of flowers. Blooming occurs in a successive manner, with individual flowers remaining open for approximately seven days, provided that irrigation water is not applied directly to the petals, as this can adversely affect flower longevity and quality. Irrigation management plays a significant role in regulating the flowering period of this species. Studies have shown that plants grown in substrates composed of sand and coconut fibre (1:1, v/v) or vermiculite and coconut fibre (1:1, v/v), maintained at a water-holding

capacity of 60–70%, exhibited earlier flowering compared to plants cultivated in the same substrates under higher moisture availability.

Pest and diseases

Adenium (desert rose) is susceptible to several insect pests, including spider mites, mealybugs, aphids, scale insects, and oleander caterpillars. These pests can generally be managed through eco-friendly approaches such as neem oil application, mild soap solutions, or manual removal in cases of localized infestation. The crop is also affected by common fungal diseases such as root rot, powdery mildew, and leaf spot, which are frequently associated with excessive moisture, poor drainage, and inadequate air circulation. Effective disease management involves maintaining dry conditions around the root zone, ensuring proper ventilation, and, when necessary, applying suitable fungicides. Preventive measures—including regulated irrigation, the use of well-drained growing media, and adequate spacing to enhance air movement—are critical, as physiologically stressed plants are more prone to pest and disease outbreaks.

Bonsai of *Adenium obesum*

Bonsai development in *Adenium obesum* begins with the selection of a healthy, vigorous seedling aged approximately 1–2 months. Early manipulation is crucial for shaping the characteristic caudex and root spread. The taproot of the selected seedling is carefully pruned using a sharp, sterilized knife to regulate vertical growth and stimulate the formation of lateral roots. The seedling is then planted in a moist, sandy and well-drained potting medium to encourage new root initiation from the cut surfaces. To promote horizontal development of secondary roots and enhance the aesthetic appeal of the caudex, a small, flat, sterilized stone is placed beneath the seedling at planting. As growth progresses, the plant is periodically repotted into wider and shallower containers, which are essential for achieving the bonsai form. Regular pruning is carried out throughout the year to maintain structure and compact growth; however, pruning should be timed carefully to ensure flowering, as blooms are produced on new shoots.

Nutrient management is achieved by applying a liquid fertilizer at half the recommended concentration once a month from spring through autumn to support healthy growth without excessive elongation. Irrigation plays a critical role in bonsai maintenance; watering is typically done every 7–10 days, allowing the growing medium to dry slightly between applications. For long-term maintenance, the bonsai should be repotted every two to three years during late spring, accompanied by root pruning to sustain plant vigor and preserve the desired miniature form.



Bonsai *Adenium*

Commercialization of *Adenium obesum*

The commercialization of *Adenium obesum* has expanded rapidly in recent years due to its high ornamental value, adaptability to container culture, and growing demand in urban horticulture. Its distinctive caudex, prolonged flowering period, and tolerance to drought make it a preferred ornamental succulent for home gardens, balconies, rooftops, and indoor decoration. The plant's suitability for bonsai culture and xeriscaping has further enhanced its market appeal, particularly in regions facing water scarcity. Commercial production of *Adenium* largely relies on vegetative propagation, especially grafting, to ensure uniformity in flower colour, form, and growth habit. Grafted plants command higher market prices compared to seed-grown plants due to their predictable flowering and superior aesthetic traits. Seed propagation, although economical and widely practiced, is mainly used for mass production and for developing new hybrids, as it results in high genetic variability.

In India and other tropical countries, *Adenium* has emerged as a profitable ornamental crop for nurseries and small-scale entrepreneurs because of its low maintenance requirements, minimal input costs, and high consumer demand. Plants are marketed at various growth stages—from seedlings to mature, flowering specimens—allowing flexibility in pricing and sales strategies. Export potential is also increasing, particularly to Southeast Asia, the Middle East, and European markets, where there is a strong preference for exotic succulents and caudiciform plants. With the rising popularity of home gardening, landscaping, and ornamental plant collections, *Adenium* offers significant opportunities for commercialization. Adoption of improved propagation techniques, standardized production protocols, and integrated pest and disease management practices can further enhance its economic viability and sustainability in the floriculture industry.

Future Prospects of *Adenium* in India

The future of *Adenium* commercialization in India appears highly promising, supported by shifting consumer preferences, innovative marketing approaches, and an increasing emphasis on sustainable horticultural practices. As growers and nurseries adapt to changing market dynamics and integrate modern technologies in production and distribution, *Adenium* is expected to emerge as an important segment within the ornamental plant industry. With strategic planning, quality assurance, and efficient supply-chain management, stakeholders can effectively harness the considerable economic potential offered by this versatile ornamental species. The commercial prospects of *Adenium* (desert rose) in India are further strengthened by its distinctive aesthetic appeal, climate adaptability, and expanding consumer base. Growing interest in home gardening, balcony and rooftop landscaping, and bonsai culture has created sustained demand for compact, low-maintenance ornamental plants. These factors, combined with the plant's affordability and ease of cultivation, position *Adenium* as a viable and profitable crop for both small-scale growers and commercial enterprises.

Conclusion

The rising demand for *Adenium* in Indian markets reflects a broader trend toward ornamental gardening, driven by urbanization, lifestyle changes, and an increasing appreciation for visually appealing yet easy-to-maintain plants. Its vibrant floral display, unique caudex structure, and adaptability to container culture make *Adenium* a preferred choice for enhancing both indoor and outdoor spaces. Affordable pricing further broadens its appeal, attracting a diverse consumer base ranging from dedicated gardening enthusiasts to casual plant buyers. The expansion of e-commerce platforms and the growing presence of local nurseries have significantly improved accessibility,

allowing wider dissemination of planting material and cultivation knowledge. Although challenges remain in terms of technical expertise and consistent quality supply, the scope for growth in both domestic and international markets remains substantial. By emphasizing standardized production practices, superior plant quality, and targeted marketing strategies, *Adenium* can be positioned not merely as an ornamental plant but as an integral component of contemporary home décor and gardening culture in India. With increasing interest in bonsai and exotic ornamentals, *Adenium* is well poised to become a staple in Indian homes and gardens, offering a lucrative and sustainable opportunity for growers and marketers alike.

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WHY FUTURE CROPS MUST SURVIVE WITH LESS WATER

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Abstract

Water is the most critical resource for agriculture, yet it is becoming increasingly scarce due to climate change, rapid population growth, and decades of unsustainable water use. Rising global temperatures, erratic and unpredictable rainfall patterns, shrinking glaciers, and more frequent and intense droughts are drastically reducing the availability of freshwater for crop production. At the same time, the demand for food is continuously increasing, placing unprecedented pressure on already limited water resources. Future agriculture cannot depend on abundant irrigation or stable rainfall. Instead, it must rely on crops that can grow, yield, and survive with less water while maintaining productivity and quality. This article discusses why developing water-efficient and drought-tolerant crops is essential, how plants naturally respond and adapt to water stress, and how modern science and plant breeding are shaping the next generation of climate-resilient crops. It also highlights future directions and innovations required to build a sustainable, water-smart agricultural system capable of feeding a growing global population under changing climates.

Keywords: Climate change; Water scarcity; Drought tolerance; Climate-resilient crops; Water-use efficiency; Sustainable agriculture.

Introduction

Water has always been the foundation of agriculture. From the earliest river-valley civilizations to modern irrigated farming systems, access to water has determined where crops can be grown and how much food can be produced. For centuries, relatively predictable rainfall, rivers, lakes, and groundwater supported crop production and human civilization. Today, however, this foundation is weakening at an alarming rate. Climate change is disrupting rainfall patterns, increasing evaporation losses, intensifying droughts, melting glaciers, and shrinking both surface and underground freshwater resources. In many agricultural regions, water tables are rapidly falling, irrigation costs are rising, and competition for water between cities, industries, and farms is becoming more severe.

Under these conditions, the future of agriculture cannot be built on water-intensive crops and conventional practices that assume unlimited water availability. Instead, it must focus on developing crops that can maintain growth, productivity, and reproduction under limited and uncertain water supply. The ability of crops to survive, grow, and reproduce with less water is no longer optional it is essential for ensuring long-term food security, protecting farmer livelihoods, and maintaining environmental sustainability. Building such crops represents a major shift in agricultural thinking, where resilience and efficiency are as important as yield potential.

Why Water Scarcity Is the New Agricultural Reality

Agriculture consumes nearly 70% of global freshwater withdrawals, making it the largest user of water worldwide. However, climate change is fundamentally altering the global water cycle, leading to longer dry seasons, unpredictable rainfall events, sudden floods followed by droughts, declining soil moisture, and reduced groundwater recharge. Many traditional cropping systems were developed under relatively stable climatic conditions and are poorly adapted to these extremes. As a result, even traditionally productive regions are increasingly exposed to water stress. Drought stress affects plants at every stage of growth from seed germination and seedling establishment to flowering, grain filling, and final yield. Water deficit reduces photosynthesis, limits carbon assimilation, disrupts nutrient uptake, alters hormonal balance, weakens plant structure, and accelerates leaf senescence. Prolonged or repeated droughts also degrade soil health, reduce microbial activity, increase salinity, and intensify land degradation. As water becomes scarcer and rainfall more unreliable, crops that cannot tolerate stress will fail more frequently, making farming riskier, less predictable, and less profitable especially for smallholder farmers and in rainfed agro-ecosystems.

How Plants Cope with Less Water

Plants are not helpless under drought. Over millions of years of evolution, they have developed diverse and highly sophisticated strategies to cope with water shortage. Some plants reduce water loss by closing stomata, reducing leaf area, rolling leaves, and developing thicker cuticles and waxy surfaces that limit evaporation. Others improve water capture through deeper, more extensive, and more plastic root systems capable of accessing moisture from deeper soil layers.

Certain plants adjust their metabolism under drought by accumulating compatible solutes such as proline, glycine betaine, and soluble sugars, which protect proteins and membranes. They enhance antioxidant systems to reduce oxidative damage and activate stress-responsive genes that help maintain cellular stability even when tissues lose water. At the physiological and molecular level, drought triggers complex signalling networks involving phytohormones such as abscisic acid, transcription factors, and protective proteins that reprogram growth, survival, and recovery mechanisms.

Key drought-adaptive traits include:

- Deep, dense, and efficient root systems
- Early maturity and the ability to escape terminal drought
- High water-use efficiency and reduced transpiration losses
- Osmotic adjustment and accumulation of stress-protective compounds
- Maintenance of photosynthesis and membrane stability under stress
- Strong association with beneficial soil microbes that enhance water and nutrient uptake

Understanding, identifying, and combining these traits enables scientists and breeders to design crops that perform more reliably under water-limited environments.

Science and Breeding for Water-Efficient Crops

Modern agriculture is undergoing a profound paradigm shift—from a primary focus on yield maximization under ideal conditions to resilience-centered crop improvement aimed at sustaining productivity under environmental stress. With climate change intensifying drought frequency, heat waves, and rainfall uncertainty, plant breeding today is no longer only about producing more, but about producing reliably. Contemporary breeding programs now integrate classical breeding

approaches with plant physiology, stress biology, high-throughput phenotyping, molecular markers, and advanced genomic technologies to accelerate the development of drought-tolerant and climate-resilient varieties. Techniques such as marker-assisted selection, genomic selection, genome-wide association studies, transcriptomics, proteomics, metabolomics, and CRISPR-based gene editing are transforming how breeders discover, validate, and deploy drought-adaptive genes and regulatory networks. These tools enable the precise dissection of complex drought-tolerance mechanisms and allow breeders to combine multiple adaptive traits into elite genetic backgrounds more efficiently than ever before. At the trait level, emphasis has expanded beyond yield to include physiological and morphological attributes that directly determine water-use efficiency and stress survival. Traits such as root system architecture, stomatal regulation, transpiration efficiency, canopy temperature depression, stay-green behavior, osmotic adjustment, and post-stress recovery capacity are increasingly incorporated as core selection criteria. These traits provide a deeper understanding of how plants capture water, maintain cellular stability, and sustain photosynthesis under moisture-limited environments.

Parallel advances in phenotyping have revolutionized drought research. Automated phenotyping platforms, remote sensing tools, unmanned aerial vehicles (UAVs), thermal and hyperspectral imaging, and AI-based data analysis now allow breeders to screen thousands of genotypes rapidly and non-destructively under both controlled and field drought conditions. This has significantly improved selection accuracy, reduced breeding cycles, and strengthened the link between genotype and field performance. Equally important is the integration of superior genetics with improved agronomic practices. Conservation agriculture, residue mulching, precision nutrient management, deficit and supplemental irrigation strategies, micro-irrigation systems, and approaches that enhance soil organic matter are increasingly being combined with drought-tolerant varieties to optimize water capture, retention, and utilization. Such systems-based approaches ensure that genetic gains are fully realized at the farm level.

The real breakthrough lies not in genetics or management alone, but in their integration. The future of drought-resilient agriculture depends on aligning improved crop varieties with water-efficient, soil-centered, and climate-smart farming systems that maximize productivity while minimizing risk—ensuring that every drop of water contributes to stable yields and sustainable food production.



Future Aspects: Toward Water-Smart Agriculture

The future of agriculture will revolve around the principle of “more crop per drop.” Water-smart farming will integrate crop genetics, digital technologies, and sustainable management strategies. Crops will be designed not only to tolerate drought but also to optimize water capture, transport, and utilization throughout their life cycle.

Future directions include:

- Development of climate-ready crop varieties with optimized, deeper, and more plastic root systems
- Use of artificial intelligence, modeling, sensors, and decision-support systems to match crops with soil-water conditions
- Greater reliance on dryland and low-input breeding programs targeting marginal environments
- Integration of plant–microbe technologies to enhance water uptake, stress signaling, and root growth
- Exploration of wild relatives and landraces as reservoirs of drought-adaptive genes
- Policy, institutional, and breeding efforts focused on region-specific climate adaptation

These innovations will reduce agriculture’s dependence on heavy irrigation, improve resilience of cropping systems, and help farming remain productive under uncertain and extreme climatic conditions.

Conclusion

Water scarcity is redefining the rules of agriculture. In a world where freshwater resources are shrinking, groundwater is declining, and climate uncertainty is intensifying, the survival of future crops will depend largely on their ability to grow, yield, and recover under limited water availability. Developing drought-tolerant and water-efficient crops is no longer just a scientific ambition it is a global necessity. By integrating plant breeding, modern biotechnology, digital tools, and sustainable crop management, agriculture can move toward a resilient, water-smart future. Crops that survive and yield under water-limited conditions will protect food security, stabilize farmer incomes, and reduce pressure on the planet’s most precious natural resource. The future of farming will not belong to crops that demand more water, but to those that can thrive with less.

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HORTICULTURAL PRACTICES OF ASIATIC *Lilium*

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Abstract

Asiatic lilies (*Lilium* spp.) are among the first commercially successful hybrid lilies, valued for their vibrant, diverse flower colours, robust growth, and adaptability to varied climates. This article provides a comprehensive overview of their production technology, including optimal climate and soil requirements, planting density, propagation methods, and intercultural practices. Key operations such as staking, earthing up, and irrigation management are highlighted to ensure healthy growth and high-quality flower production. Harvesting techniques are discussed with respect to market requirements, alongside post-harvest handling, grading, packaging, and storage to maximize vase life. The article also addresses major pests and diseases, offering integrated management strategies. With yields of 30–40 stems per m²/year under well-managed conditions, the adoption of scientifically validated cultivation practices enhances productivity, flower quality, and economic returns, positioning Asiatic lily as a promising crop for both domestic and export floriculture markets.

Introduction

Within the genus *Lilium*, two major horticultural groups are recognized: Oriental and Asiatic lilies. This discussion focuses specifically on the Asiatic group, which represents the first commercially successful hybrid lilies. Asiatic lilies possess a chromosome number of $2n = 24$ and are members of the family Liliaceae. The group is native to regions of East Asia and Europe, including China, Japan, Korea, and parts of Europe. These hybrids have originated through the interspecific hybridization of twelve primary species, namely *Lilium amabile*, *L. bulbiferum*, *L. concolor*, *L. dauricum*, *L. davidii*, *L. hollandicum*, *L. maculatum*, *L. leichtlinii*, *L. pumilum*, and *L. tigrinum*.

Asiatic lily cultivars are highly esteemed in floriculture due to their remarkable diversity in flower colour, ranging from vivid yellows, oranges, pinks, and reds to pure whites and striking bicoloured forms. Despite their visual appeal, they are generally non-fragrant. In India, Asiatic lilies are commercially cultivated across multiple regions that provide favourable climatic and altitudinal conditions. These include the Nilgiris (Coonoor, Ooty, Kothagiri), Kalvarayan Hills (Karumanthurai), Kodaikanal, Shevroy Hills (Yercaud), as well as parts of Himachal Pradesh (Shimla, Kullu), Kerala (hill ranges of Wayand Idukki) and the northeastern states including Arunachal Pradesh and Manipur, and Jammu & Kashmir.

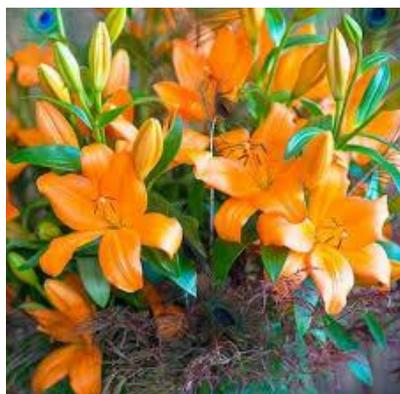
The increasing popularity of Asiatic lilies in India is attributed to their large, visually striking flowers, which demonstrate resilience and capacity for rehydration even after extended periods of

transportation. Their adaptability to diverse climatic conditions, combined with high ornamental value, underpins their growing significance in commercial floriculture and makes them a promising crop for both domestic markets and potential export opportunities.

Varieties

The Asiatic lily group encompasses a vast array of hybrid varieties, each exhibiting distinctive floral characteristics and vibrant colouration. Some of the commercially and horticulturally significant cultivars include *Pollyana* (yellow), *Dreamland* (yellow), *Nove Canto* (yellow), *Eremo* (orange), *Connecticut King* (yellow), *Elite* (orange), *Vivaldi* (pink), *Navona* (white), *Yellow Giant* (yellow), *Litouwen* (white), *Brunello* (orange), and *Blackout* (deep red).

Other notable cultivars frequently cultivated in floriculture include *Apeldoorn*, *Prato*, *Solemio*, *Grand Paradise*, *Cordellia*, *Mercedes*, and *Novcento*. These hybrids are particularly valued for their uniform growth, large and showy blooms, and adaptability to various climatic and cultivation conditions, making them a preferred choice for both commercial production and ornamental gardening.



Eremo



Blackout



Navona

Climate requirements

Asiatic lilies are typically cultivated under protected conditions such as polyhouses or shade net houses to regulate environmental factors. Optimal growth and flower production are achieved at maximum day temperatures of 21–25°C and night temperatures of 12–15°C. Lilies perform well under relatively low light intensities of 2,000–3,000 foot-candles, necessitating the use of shade nets to modulate sunlight exposure—reducing light by approximately 75% during summer and 50% during winter. Relative humidity within the greenhouse should be maintained at 80–85% to promote healthy growth. Sandy loam soils with a pH range of 6.0–7.0 are considered most suitable for bulb development.

Planting time

The timing of bulb planting varies with regional climatic conditions. In the northern plains of India, planting is generally carried out between October and November, whereas in hilly regions, suitable planting periods extend from March and again from July to September. Proper timing ensures synchronized sprouting, uniform flowering, and optimal bulb growth.

Soil and growing medium

Preparation of the growing medium is critical for successful lily cultivation. Fields should be deeply tilled, ensuring a well-aerated, sandy loam soil with a pH between 7.0 and 8.0. Organic matter should be incorporated at 4–5 kg/m² to enhance soil fertility and structure. In heavy or clay soils,

sand amendment is necessary to improve drainage, as waterlogging can lead to significant bulb losses. Efficient drainage is therefore an essential requirement to maintain bulb health and prevent rot.

Planting density

For optimal growth, Asiatic lily bulbs should be planted at a depth of 6–8 cm in a well-moistened growing medium, maintaining a spacing of 10 cm between bulbs and 20 cm between rows. Prior to planting, the medium must be thoroughly watered, and thereafter, soil moisture should be consistently maintained at an optimal level—sufficiently moist but not waterlogged—until the bulbs sprout. Proper planting density ensures uniform growth, healthy bulb development, and maximized flowering potential.

Propagation

Asiatic lilies can be propagated through multiple methods, including seeds, scales, bulblets, and bulbils. For large-scale commercial production, tissue culture techniques are increasingly employed due to their efficiency and ability to produce disease-free plants. Conventionally, lilies are propagated by division of bulblets that form at or just below the soil surface on the mother bulb. These bulblets, when separated and replanted, develop into flowering-size bulbs within one growing season, providing a reliable method for maintaining desirable horticultural traits.

Intercultural operations

Maintaining uniform soil moisture is critical, particularly during the initial three weeks after planting, to ensure proper sprouting and early growth. Irrigation should be adjusted according to crop requirements and prevailing climatic conditions. Regular weeding is essential to reduce competition for nutrients and moisture, with occasional light hoeing recommended to improve soil aeration and maintain an optimal growing environment. These intercultural practices contribute significantly to the establishment, vigor, and productivity of Asiatic lily crops.

Staking : Staking is an important operation particularly when the stem length is above 80cm. staking can be done with nylon netting, hessian string or flexible bamboo sticks.

Earthing up : Intercultural operations like earthing up was done 15 days after planting to cover up the exposed bulbs and nodes.

Harvesting : Asiatic lilies reach harvest maturity approximately 90–120 days after planting, with the timing of harvest carefully adjusted according to the intended market. For local markets, stems are typically harvested when 1–2 florets have just opened. For distant markets, stems should be cut when the lower-most buds are fully developed and begin to show colour but have not yet opened, as fully opened buds are more susceptible to mechanical damage during transport. Immediately after cutting, stems should be placed in cold water to maintain freshness and prolong post-harvest quality. Under proper handling, the vase life of Asiatic lily stems ranges from 7 to 14 days.

Grading : Post-harvest, Asiatic lily stems are graded based on two key parameters: stem length and the number of flower buds per stem. Additionally, leaves from the bottom 10–15 cm of each stem is removed to reduce microbial contamination and improve the longevity and overall keeping quality of the flowers. This careful grading process ensures uniformity and enhances the commercial value of the harvested stems.

Packaging, transportation, and storage

The post-harvest longevity and quality of Asiatic lily stems can be significantly enhanced through careful handling and storage. Wrapping freshly cut stems in butter paper and storing them at 4°C

for up to six days preserves flower quality without adversely affecting vase life. Typically, 10–12 stems are securely bundled at the base using tape or rubber bands and then wrapped in newspaper to provide cushioning during transport. These bundles are subsequently packed into standard-sized cartons and shipped in refrigerated containers, ensuring minimal mechanical damage and maintaining optimal freshness during distribution.

Yield : Under well-managed cultivation conditions, Asiatic lilies can yield approximately 30–40 flower stems per square metre annually, depending on the cultivar, climate, and cultural practices.

Plant protection

Pests

Aphids: Infestation is characterized by curling and deformation of young leaves, with green spots appearing on buds, leading to malformed flowers that may remain partially green. Management includes spraying Imidacloprid 17.8% SL at 1 ml/l or Chlorpyrifos at 2 ml/l, ensuring thorough coverage of affected areas.

Mites: Mites feed on small buds, causing damage and stunted flower development. Control can be achieved by applying Wettable Sulphur at 1.5 g/l, sprayed directly onto infested buds and foliage.

Diseases

Bulb and Scale rot: Initial symptoms include brown discoloration on the top and sides of bulbs, eventually leading to rot and stunted growth. Prevention involves maintaining minimal soil moisture, regulating greenhouse temperature, and removing infected bulbs or scales. Chemical management can be done by drenching the soil with Carbendazim at 1 g/l.

Root rot: Manifested as decayed roots and poor plant vigor, this disease can be managed by soil drenching with Metalaxyl at 0.1%, combined with proper drainage and avoiding water stagnation.

Conclusion

Adopting scientifically validated cultivation practices for Asiatic lily enables the production of high-quality flowers while optimizing yield and resource use. Such structured approaches not only improve overall productivity but also contribute to economic benefits for growers, enhancing livelihoods and supporting sustainable floriculture development.

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ETHYLENE MANAGEMENT IN FLORICULTURE

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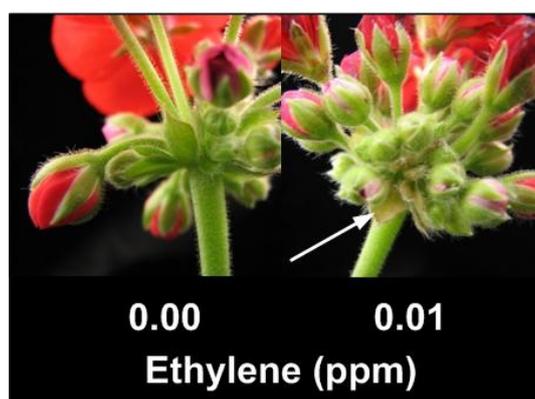
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Abstract

Floriculture is a rapidly expanding sector of horticulture, where the market value of cut flowers depends largely on freshness, appearance, fragrance, and vase life. However, post-harvest deterioration remains a major challenge, with ethylene acting as a key factor accelerating flower senescence even at very low concentrations. Ethylene exposure leads to wilting, petal abscission, yellowing, premature opening, and reduced shelf life in many ethylene-sensitive ornamental crops such as carnation, rose, lily, gerbera, orchid, and chrysanthemum. Ethylene in the supply chain originates from flower metabolism, mechanical injuries, ripening fruits, vehicle exhaust, and poor ventilation. Effective ethylene management involves low-temperature storage, pre-cooling, adequate ventilation, and the use of chemical treatments such as 1-methylcyclopropene (1-MCP) and vase solution additives like 8-hydroxyquinoline citrate (8-HQC) and sulphate (8-HQS). Proper vase solution management, careful handling, and hygienic practices further reduce ethylene-related damage. Adoption of integrated ethylene management strategies significantly extends vase life, minimizes post-harvest losses, and enhances the quality, profitability, and sustainability of the floriculture industry.

Introduction

Floriculture is one of the fastest-growing sectors of horticulture, providing employment, income, and aesthetic value worldwide. The commercial success of cut flowers depends largely on their freshness, colour, fragrance, and vase life. However, flowers are highly perishable commodities, and their quality begins to decline immediately after harvest. Among the various factors responsible for post-harvest deterioration, ethylene plays a crucial role. Ethylene management has therefore become an essential component of modern floriculture to reduce losses and ensure better market returns.



Ethylene-The Invisible Enemy

Ethylene is a naturally occurring gaseous plant hormone involved in several physiological processes such as fruit ripening, leaf abscission, and flower senescence. In floriculture, ethylene is mainly associated with ageing and deterioration of flowers. Even at extremely low concentrations, ethylene can cause irreversible damage to sensitive flowers. Its gaseous nature makes it difficult to detect, but its effects are clearly visible in the form of wilting, petal drop, yellowing of leaves, premature flower opening, and shortened vase life.

Ethylene Sensitivity of Flowers

Different ornamental crops vary in their sensitivity to ethylene. Flowers such as carnation, rose, orchid, lily, gerbera, and chrysanthemum are highly sensitive and show rapid quality loss when exposed to ethylene. In these flowers, ethylene accelerates senescence, leading to reduced shelf life and poor consumer acceptance. Therefore, understanding crop-specific ethylene responses is important for adopting suitable management strategies.



Sources of Ethylene in the Supply Chain

Ethylene present in the floriculture supply chain originates from multiple sources. Flowers themselves produce ethylene as part of their natural metabolism, especially under stress conditions. Mechanical injury during harvesting, grading, and packing increases ethylene production. Ripening fruits stored near flowers release large amounts of ethylene, which can severely affect flower quality. In addition, vehicle exhaust fumes, smoke, and poor ventilation in storage rooms and transport vehicles contribute to ethylene accumulation. Proper identification and control of these sources are critical for effective ethylene management.

Role of Temperature and Ventilation

Temperature management is one of the most effective methods to control ethylene production and action. Low-temperature storage reduces respiration rate and slows down ethylene synthesis in flowers. Cold storage facilities help in delaying senescence and maintaining flower freshness during storage and transportation. Pre-cooling immediately after harvest further enhances the effectiveness of cold storage. Along with temperature control, adequate ventilation is equally important. Good air circulation prevents the buildup of ethylene gas and maintains a healthy storage environment.

Chemical Methods for Ethylene Control

Chemical treatments are widely used to manage ethylene effects in floriculture. Silver thiosulphate (STS) has been traditionally used to block ethylene action by inhibiting ethylene receptors in plant tissues. Although effective, its use is limited due to environmental and health concerns. As a safer

alternative, 1-methylcyclopropene (1-MCP) is now commonly used because it effectively prevents ethylene from binding to its receptors even at very low concentrations. In addition, chemicals like 8-hydroxyquinoline citrate (8-HQC) and 8-hydroxyquinoline sulphate (8-HQS) are used in vase solutions to improve water uptake, reduce microbial growth, and indirectly delay ethylene-induced senescence.

Vase Solution Management

Vase solutions play an important role in extending the post-harvest life of cut flowers. Sucrose is commonly added as an energy source to support bud opening and colour development. When combined with antimicrobial and anti-ethylene compounds, vase solutions significantly improve vase life and overall flower quality. Maintaining clean water, using correct chemical concentrations, and regularly replacing vase solutions are essential practices at the retail and consumer levels.

Importance of Careful Handling

Proper handling practices throughout the post-harvest chain help minimize ethylene-related damage. Harvesting flowers at the correct stage of maturity, avoiding mechanical injuries, removing damaged or diseased flowers, and maintaining cleanliness during handling and storage reduce stress-induced ethylene production. Training farmers, workers, and traders in post-harvest management is therefore vital for effective ethylene control.

Conclusion

Ethylene management is a key aspect of post-harvest technology in floriculture. Although ethylene is a natural plant hormone, its harmful effects on flower quality can be effectively reduced through temperature management, proper ventilation, chemical treatments, vase solution practices, and careful handling. Adoption of these simple and scientifically proven methods helps extend vase life, reduce post-harvest losses, and improve economic returns. Effective ethylene management not only enhances flower quality but also contributes to the sustainability and profitability of the floriculture industry.

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IMPORTANCE OF NURSERY MANAGEMENT IN VEGETABLE FARMING

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Abstract

A crucial fundamental technique in vegetable production, nursery management has a direct impact on crop output, field establishment, and seedling quality. In order to lower transplant shock and increase survival rates, well-run nurseries provide consistent, robust, and healthy seedlings that are resistant to biotic and abiotic challenges. To produce high-quality seedlings for a variety of vegetable crops, including tomato, chilli, brinjal, cabbage, cauliflower, onion, and capsicum, scientific nursery techniques such as ideal site selection, sterile and balanced growing media, seed treatment with bio-agents, precise sowing, controlled irrigation, nutrient management, and seedling hardening are crucial. Pro-tray and cocopeat-based nurseries, grafted seedlings, bio-input integration, and computerized commercial nursery systems are examples of recent advancements that have further enhanced labor efficiency, disease resistance, and seedling uniformity. Adoption of these techniques promotes sustainable and climate-resilient farming while resulting in faster crop establishment, increased yield potential, lower input costs, and substantial economic rewards. In order to improve seedling quality, farm profitability, and resource-use efficiency in contemporary horticulture systems, this study integrates the most recent research and advancements in vegetable nursery management.

Introduction: Why Nursery Management Matters

The main field is planted much later in the vegetable planting process. Many farmers experience poor crop stand, uneven growth, severe pest and disease attack, and low yield even with high-quality fertilizers and herbicides. One of the primary reasons of this problem is low-quality seedlings. Weak, ill, or uneven seedlings cannot perform well in the field.

Nursery management is crucial for producing robust, healthy, and reliable seedlings. A well-managed nursery ensures better post-transplant survival, early crop establishment, and higher yield. Due to rising input costs, unpredictable weather, and increased pest impact, raising high-quality seedlings is now more important than ever for successful vegetable production.

Nursery Management in Vegetable Crops

Concept and Meaning of a Nursery

Vegetable seeds are sown in a nursery, which is a specifically constructed and well-managed space where seedlings are nurtured under carefully monitored circumstances until they reach the proper

stage for transplanting into the main field. In order to guarantee consistent germination, good seedling growth, and early plant vigor, nursery management entails controlling environmental elements including moisture, temperature, light, and fertilizer availability. Crop establishment, overall production, and seedling quality are all greatly impacted by proper nursery methods.

Importance of Raising Vegetables in Nurseries

Several vegetable crops, including tomato (*Solanum lycopersicum*), chilli (*Capsicum annuum*), brinjal (*Solanum melongena*), cabbage (*Brassica oleracea* var. *capitata*), cauliflower (*Brassica oleracea* var. *botrytis*), onion (*Allium cepa*), and capsicum, are commonly raised in nurseries due to their sensitivity during the early growth stages. During germination and early growth, when seedlings are particularly susceptible to biotic and abiotic stressors, nursery rearing enables intense care. Seedlings are shielded from harsh weather, excessive rainfall, soil-borne illnesses, and insect pests under controlled nursery settings.

Role of Nursery Management in Crop Establishment

Better field establishment and coordinated crop growth are ensured by nursery management, which makes it easier to choose healthy, consistent, and disease-free seedlings for transplantation. Using high-quality seedlings increases the likelihood of survival following transplantation, increases the efficiency of fertilizer and water consumption, and increases the potential yield. Therefore, in both open-field and protected cultivation settings, nursery management is a fundamental technique for efficient and sustainable vegetable production systems.

Importance of Nursery Management in Vegetable Farming Production of Healthy and Uniform Seedlings

The development of robust, healthy seedlings that are consistent in size, age, and physiological state is ensured by effective nursery management. Uniform flowering, fruit set, and harvesting result from coordinated crop establishment in the field, which is facilitated by uniform seedlings. This consistency raises marketable production quality and increases crop management effectiveness.

Improved Germination and Seedling Survival

Optimal growth media, moisture control, and disease control are just a few of the scientific nursery techniques that greatly increase seed germination rates while reducing seed waste. Stronger root systems and improved physiological resilience are characteristics of seedlings cultivated in regulated nurseries, which lead to higher transplant survival rates and lower seedling mortality.

Early Crop Establishment and Higher Yield

After being transplanted, seedlings generated with good nursery management settle quickly, allowing for early vegetative growth and timely reproductive development. Early establishment results in earlier blooming and harvesting, which prolongs the productive season and boosts overall yield and financial gains.

Efficient Utilization of Agricultural Inputs

Critical inputs including seed, water, fertilizer, and plant protection chemicals are used as efficiently as possible in well-run nurseries. Nursery management promotes resource-use efficiency and sustainability in vegetable production systems while lowering cultivation costs overall by decreasing input waste and the requirement for corrective actions in the main field.

Types of Vegetable Nurseries

Open Nursery

The traditional way of producing vegetable seedlings is represented by open nurseries, where seeds are put directly on prepared soil beds in a natural setting. Because of its ease of use and minimal

setup costs, this system is frequently used. However, in addition to soil-borne diseases and insect pests, seedlings produced in open nurseries are subjected to a variety of climatic conditions, including high temperatures, wind stress, and heavy rains. As a result, especially in intensive vegetable production systems, open nurseries frequently encounter inconsistent germination, increased seedling mortality, and fluctuating seedling quality.

Protected Nursery

Raising seedlings in regulated or semi-controlled environments, such as shade nets, polyhouses, or low tunnels, is known as protected nurseries. By controlling temperature, light intensity, and humidity, these buildings modify the microclimate and offer defense against heavy rainfall, heat stress, and insect vectors. In addition to lowering disease incidence and pesticide reliance, protected nursery systems greatly increase seedling health, uniformity, and survival rate. Because of these benefits, commercial and high-value vegetable production is increasingly using protected nurseries.

Raised Bed and Pro-tray Nursery Systems

Elevated growth platforms or containers filled with sterile or soilless growing medium, such as cocopeat, vermiculite, or substrates based on compost, are used in raised bed and pro-tray nursery systems. These solutions efficiently reduce soil-borne illnesses, enhance aeration and drainage, and encourage consistent root growth. Specifically, pro-tray nurseries provide for easy handling during transplanting, accurate seed positioning, and effective use of available space. Raised bed and pro-tray nurseries are therefore regarded as extremely effective systems for growing vegetable seedlings that are disease-free, healthy, and ready for transplantation.

Step-by-Step Nursery Management Practices

Selection of Nursery Site

For seedling production to be effective, a suitable nursery location must be chosen. To avoid waterlogging and related root diseases, the nursery area should have well-drained soil. For healthy seedling growth and a decrease in the prevalence of fungal diseases, enough solar exposure and adequate air circulation are crucial. To reduce pathogen carryover and guarantee the generation of healthy, disease-free seedlings, the location should be far from fields with a history of soil-borne illnesses.

Preparation of Growing Media

To promote consistent germination and robust root development, the perfect nursery growing medium should be loose, porous, fertile, and pathogen-free. Soil, sand, and farmyard manure (FYM) combined in a 1:1:1 ratio is an often suggested growth medium that offers balanced aeration, drainage, and nutrient availability. Cocopeat-based soilless media are popular for pro-tray nursery systems because of their excellent water-holding capacity, sterility, and advantageous physical characteristics that support uniform seedling development and good root growth.

Seed Selection and Seed Treatment

To produce consistent and robust seedlings, certified, premium seeds with a high germination potential must be used. In order to shield seedlings from soil-borne and seed-borne diseases during their early development phases, seed treatment is an essential preventive step. To improve seedling health and lower disease incidence, biological seed treatments employing antagonistic bacteria like *Pseudomonas fluorescens* or *Trichoderma* spp. are frequently used. Additionally, under nursery settings, hot water seed treatment is a physical procedure that effectively reduces seed-borne infections, boosting germination and seedling vigor.

Sowing of Seeds

Seeds should be sown in straight lines or designated cells to facilitate uniform spacing, easy intercultural operations, and effective plant protection. Sowing too deeply might delay emergence and lower germination, thus it's important to choose the right depth. To lessen competition for light, nutrients, and moisture and to lower the prevalence of nursery illnesses, seedlings should not be overcrowded.

Water Management

During nursery growing, effective water management is essential. To keep sufficient moisture without producing waterlogging, light and regular irrigation should be supplied. Damping-off and other fungal illnesses are more likely to occur when there is too much moisture. Rose cans, mist irrigation, and drip systems are recommended irrigation techniques because they provide even moisture distribution and reduce physical harm to young plants.

Management of Nutrients

For quick and healthy growth, nursery seedlings need nutrients that are easily available and in balance. Without producing nutritional toxicity, the use of diluted water-soluble fertilizers promotes early seedling growth. Improved root development, physiological activity, and general seedling vigor are further enhanced by the application of liquid organic manures and biostimulants, which improves transplant success.

Plant Protection Measures

Nursery seedlings are highly susceptible to diseases, particularly damping-off, which is commonly associated with excess moisture and poor aeration. Preventive measures such as maintaining optimal moisture levels, ensuring good drainage, and avoiding dense sowing are essential. The use of bio-fungicides is preferred over heavy chemical pesticides to manage nursery diseases, as they are environmentally safe and promote beneficial microbial activity.

Hardening of Seedlings

Hardening of seedlings is a crucial practice prior to transplanting to enhance their adaptability to field conditions. This process involves gradual reduction of irrigation and controlled exposure of seedlings to increased sunlight and ambient environmental conditions. Proper hardening improves seedling resilience, reduces transplant shock, and significantly enhances survival and establishment in the main field.

Recommended Inputs and Practices for Vegetable Nurseries

The production of healthy and uniform vegetable seedlings requires strict adherence to crop-specific seed rates to prevent overcrowding, minimise disease incidence, and ensure optimal seedling growth. The selection of appropriate growing media is critical: conventional nurseries typically employ a soil-sand-farmyard manure mixture (1:1:1), whereas modern pro-tray nurseries favour cocopeat-based soilless substrates, which provide sterility, uniform texture, and enhanced root development. Integration of biological agents, such as *Trichoderma* spp. and *Pseudomonas fluorescens*, is recommended as a preventive strategy to suppress soil- and seed-borne pathogens and improve seedling vigour in an environmentally sustainable manner. Nursery duration should be tailored to the specific crop, with tomato, chilli, and brinjal seedlings ready for transplanting in 25-30 days; cabbage and cauliflower in 30–35 days; and onion in 40-45 days. Transplanting at the optimal physiological stage ensures superior field establishment, uniform growth, and enhanced yield potential.

Do's and Don'ts in Nursery Management

S. No.	Do's	Don'ts
1	Use raised beds or pro-trays for uniform growth and good drainage	Do not overcrowd seedlings, as it reduces growth and increases disease incidence
2	Treat seeds before sowing with recommended fungicides or bio-agents	Avoid over-irrigation, which can lead to waterlogging and root diseases
3	Maintain optimum soil moisture for proper germination	Do not use infected, old, or poorly sterilized soil, which may harbor pathogens
4	Provide adequate sunlight or shade as per crop requirement	Avoid exposing seedlings to extreme sunlight or shade
5	Use balanced growing media (soil:sand:FYM 1:1:1 or cocopeat-based media)	Do not neglect nutrient requirements; poor media reduces seedling vigor
6	Apply bio-agents like <i>Trichoderma spp.</i> and <i>Pseudomonas fluorescens</i>	Do not use chemical pesticides unnecessarily, which can harm beneficial microbes
7	Maintain clean and sanitized nursery tools and beds	Avoid using contaminated tools, which spread pathogens
8	Ensure proper ventilation to reduce humidity and fungal growth	Do not allow stagnant water to accumulate around seedlings
9	Harden seedlings before transplanting by gradually exposing them to field conditions	Do not transplant weak or immature seedlings, which reduces survival and yield
10	Monitor seedlings regularly for pests and diseases	Do not ignore early signs of stress or disease

Recent Innovations in Nursery Management

Improving seedling quality, lowering losses, and encouraging sustainable practices have been the main goals of recent developments in vegetable nursery management. Strong root development, consistent seedling growth, and good survival rates are made possible by pro-tray and cocopeat technology. Grafted vegetable seedlings increase output potential and enhance resistance to soil-borne illnesses, especially in tomatoes, brinjal, and cucurbits. Using bio-inputs, such as microbial consortia and environmentally benign biofertilizers, lessens the need for chemical treatments while enhancing rhizosphere health. Agri-entrepreneurs may now provide ready-to-transplant seedlings, saving farmers time and effort while guaranteeing constant seedling quality thanks to the emergence of commercial and digital nursery systems.

Field-Level Applications, Common Issues, and Economic Impact of Nursery Management

Adoption of modern nursery practices, such as pro-tray systems, has led to 90–95% seedling survival, earlier harvesting, and increased farm income, while small nursery units have emerged as profitable ventures for rural entrepreneurs. Common nursery problems, including damping-off disease, weak seedlings, and poor germination, can be effectively mitigated through raised beds, seed treatment, balanced nutrition, and use of quality seeds. Efficient nursery management directly translates to economic benefits, including reduced crop failure, lower cultivation costs, improved

yield, and higher net profit, while simultaneously providing avenues for nursery-based entrepreneurship.

Scientific nursery practices also contribute to sustainable vegetable farming by minimizing pesticide use, conserving resources, and promoting climate-resilient, eco-friendly cultivation. Key take-home messages include: healthy nurseries produce healthy crops, seedling quality determines final yield, and nursery management is a low-cost, high-return practice. Practical recommendations emphasize raising seedlings on raised beds, preferring bio-inputs over chemicals, and transplanting seedlings at the recommended age with 4–6 true leaves, as these measures can improve crop success by 30–40% and enhance survival rates up to 95% in pro-tray seedlings.

Conclusion

The first stage in a good vegetable producing process is nursery management. Adopting scientific nursery procedures guarantees homogeneous crop establishment, improved resistance against biotic and abiotic challenges, and optimal seedling quality. Higher yields, increased farm revenue, and sustained cultivation are all facilitated by effective nursery management, which also encourages resource-efficient and environmentally responsible methods. Thus, investing in meticulous seedling production offers a solid and dependable basis for vegetable farming that is both lucrative and climate adaptable.

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WHAT AGRICULTURAL RESEARCH REALLY DOES FOR FARMERS

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Abstract

Agricultural research is often imagined as an activity restricted to laboratories, research farms, and universities, disconnected from the realities of everyday farming. In practice, it forms the invisible foundation of modern agriculture and quietly shapes nearly every decision made on the farm. From the development of improved crop varieties to the refinement of cultivation practices, irrigation strategies, pest management systems, and post-harvest technologies, agricultural research continuously influences what farmers grow and how they grow it. In an era defined by climate change, land and water scarcity, emerging pests and diseases, market instability, and declining soil health, the role of research has become more critical than ever. Agricultural research provides the scientific understanding needed to develop resilient crops, efficient farming systems, and sustainable food production models. By linking fundamental science with field-level application, research transforms knowledge into tools that enhance productivity, reduce vulnerability, and strengthen rural livelihoods. This article explores how agricultural research moves beyond theory to deliver practical, farmer-centered solutions that safeguard both food security and the future of farming.

Introduction

When people hear the phrase “agricultural research,” they often picture scientists in white coats working in high-tech laboratories, surrounded by microscopes, machines, and controlled environments far removed from the realities of farmers and fields. While laboratory work is an essential starting point, it is only the first step in a much longer journey. The real purpose of agricultural research is not fulfilled inside research buildings, but out in the open, where crops grow under unpredictable weather, diverse soils, and real-world constraints. Research achieves its true value only when scientific knowledge reaches the soil, the seed, and ultimately, the farmer. Every improved crop variety that reaches a farmer’s hand carries within it years sometimes decades of careful experimentation, genetic evaluation, and multi-location testing. Every fertilizer recommendation, pest-management strategy, irrigation schedule, and cropping system guideline is built upon countless field trials, laboratory analyses, and farmer-level validations. Behind what may appear to be a simple advisory lies an enormous scientific effort involving plant breeders, soil scientists, physiologists, pathologists, engineers, economists, and extension workers. Agricultural research quietly shapes what farmers grow, how they grow it, and how successfully they can respond to both opportunity and risk.

The challenges facing today’s farmers are more complex, interconnected, and unpredictable than at any other time in history. Climate change has disrupted traditional growing seasons, altered rainfall

patterns, intensified droughts and floods, and increased the frequency of extreme weather events. Rising temperatures are affecting crop physiology, water demand, and pest populations. At the same time, farmers must cope with shrinking land holdings, declining soil fertility, groundwater depletion, rising input costs, labor shortages, and rapidly evolving pest and disease pressures. Markets are volatile, production risks are higher, and the margin for error is shrinking. Under these conditions, farming is no longer only a biological activity; it is also an environmental, technological, and socio-economic challenge. Decisions made on the farm today must balance productivity, profitability, and sustainability. Agricultural research serves as a critical bridge between science and society, converting complex biological processes and technological innovations into practical, field-ready solutions. It provides farmers with the tools to adapt, the knowledge to manage risk, and the confidence to invest in the future. Far from being distant or abstract, agricultural research is embedded in nearly every farming decision made today—guiding the seeds farmers sow, the inputs they apply, the practices they adopt, and the strategies they use to survive in an increasingly uncertain world.

Developing Better Crops

One of the most visible and impactful outcomes of agricultural research is the development of improved crop varieties. Plant breeders work continuously to assemble beneficial traits from diverse genetic resources, combining traditional breeding methods with modern molecular and genomic technologies. The goal is no longer only to increase yield, but to create varieties that perform reliably under stress, use resources efficiently, and meet nutritional and market demands. For farmers, these improved crops represent security as much as productivity. Varieties tolerant to drought, heat, salinity, and flooding help stabilize harvests in the face of climate variability. Resistance to pests and diseases reduces dependence on chemical controls, lowering costs and environmental risks. Enhanced nutritional quality addresses hidden hunger, linking agricultural research directly to public health. The long journey from genetic discovery to seed distribution involves multilocation trials, participatory evaluation, and rigorous testing to ensure that new varieties truly serve farmers' needs. Each new seed released to farmers carries within it years of scientific effort and field validation.

Helping Farmers Face Climate Change

Climate change is reshaping agriculture in ways that are already visible in farmers' fields. Delayed monsoons, sudden heat waves, prolonged dry spells, and unpredictable pest outbreaks threaten the stability of traditional cropping systems. Agricultural research plays a central role in helping farmers adapt to this new reality. Scientists investigate how plants respond to environmental stress at physiological, biochemical, and genetic levels, using this knowledge to guide the development of climate-resilient crops. Beyond crop improvement, agricultural research contributes to the design of climate-smart farming systems. These include improved cropping calendars, water-conservation strategies, stress-monitoring tools, and predictive models that help anticipate extreme events. By integrating agronomy, breeding, meteorology, and data science, research offers farmers practical pathways to manage risk. This capacity to anticipate, absorb, and recover from climate shocks is increasingly vital. Through research-based innovation, farmers are not merely reacting to climate change; they are being equipped to live with it.

Improving Soil, Water, and Input Use

The sustainability of agriculture depends fundamentally on the responsible management of soil and water the two most critical resources on which all food production rests. Agricultural research

provides the scientific foundation for understanding how these resources function within cropping systems, how they are degraded, and how they can be restored and protected while maintaining long-term productivity. Decades of long-term field experiments across diverse agro-ecological regions have revealed the central role of soil organic matter, microbial communities, soil structure, and nutrient cycling in regulating crop growth, water retention, and resilience to stress. These insights have transformed soil management from a purely input-based approach to a systems-based science. Research has demonstrated how practices such as crop rotation, cover cropping, conservation tillage, residue retention, and integrated nutrient management influence soil carbon stocks, aggregation, and biological activity. This knowledge has led to improved fertilizer recommendations, site-specific nutrient management strategies, and soil-health-based advisory systems that enhance nutrient-use efficiency while minimizing losses to the environment. By strengthening the biological and physical foundation of soils, research-driven practices improve root development, water infiltration, and the capacity of fields to buffer droughts and heavy rainfall events. Similarly, research into plant-water relations, hydrology, and irrigation engineering has revolutionized water management in agriculture. Studies on crop water requirements, transpiration dynamics, and stress physiology have guided the development of precise irrigation scheduling methods and decision-support tools. Advances in irrigation technologies such as drip and sprinkler systems, sensor-based monitoring, automated delivery, and deficit irrigation strategies have enabled farmers to produce more food with significantly less water. These innovations are especially critical in arid and semi-arid regions, where groundwater depletion and competition for water increasingly threaten agricultural viability.

In parallel, integrated approaches to nutrient and pest management emerging from agricultural research are reducing excessive reliance on chemical inputs and promoting ecological balance within farming systems. Integrated nutrient management combines organic amendments, biological inputs, and mineral fertilizers to sustain soil fertility while lowering environmental footprints. Integrated pest management emphasizes surveillance, biological control, habitat management, and targeted interventions, reducing pesticide misuse and preserving beneficial organisms. Through these combined efforts, agricultural research aligns productivity goals with environmental stewardship. It ensures that intensification does not occur at the expense of soil degradation, water depletion, or ecological disruption. Instead, research enables the development of farming systems that are productive yet regenerative—capable of meeting present food demands while safeguarding the fertility, stability, and resilience of agricultural landscapes for future generations.

Turning Knowledge into Practical Solutions

The true value of agricultural research lies not in scientific publications alone, but in its translation into real-world practice. Through on-farm research, adaptive trials, and extension networks, innovations are tested under farmers' conditions and refined through feedback. This participatory process ensures that technologies are not only scientifically sound, but socially acceptable and economically feasible. Research-driven solutions now extend far beyond crop production. They include improved post-harvest systems that reduce losses, mechanization tools that reduce drudgery, digital platforms that deliver timely information, and decision-support systems that guide farm management. The boundary between researcher and farmer is increasingly blurred, with farmers contributing experiential knowledge that shapes research priorities. When science and farming communities interact closely, innovation becomes faster, more relevant, and more impactful.

Supporting Livelihoods and Food Security

Agricultural research underpins food security not only by increasing food production, but also by stabilizing farming systems and expanding livelihood opportunities across the agricultural value chain. While higher yields remain important, the deeper contribution of research lies in reducing vulnerability and uncertainty in farming. By improving productivity, enhancing resource-use efficiency, and strengthening resilience to climatic and biological stresses, agricultural research helps protect farmers from the economic shocks associated with crop failure, extreme weather events, pest outbreaks, and volatile markets. This stability is essential for small and marginal farmers, for whom a single failed season can have long-lasting consequences. Research also creates new pathways for income diversification. The development of improved crop varieties, protected cultivation technologies, integrated farming systems, and location-specific production practices enables farmers to shift toward high-value crops, off-season production, and specialized markets. Advances in post-harvest management, food processing, and quality enhancement further allow farmers to move beyond raw commodity production into value addition, branding, and agri-based enterprises. These opportunities not only increase farm income but also spread risk across multiple activities, making rural livelihoods more resilient.

Beyond the farm gate, agricultural research plays a critical role in strengthening the entire food system. Innovations in storage, packaging, cold-chain management, transportation, and food processing significantly reduce post-harvest losses, preserve nutritional quality, and improve food safety. Research-driven improvements in supply chains enhance market access, reduce price volatility, and connect farmers more effectively to consumers. In this way, agricultural research supports both producers and consumers by making food systems more efficient, reliable, and inclusive. In rural regions, these advances contribute directly to employment generation, skill development, and income growth. Research-led progress in mechanization, agribusiness development, seed production, and agro-processing stimulates local economies and creates non-farm employment opportunities, particularly for youth and women. By empowering farmers with knowledge, technology, and institutional support, agricultural research facilitates a gradual transition from subsistence-oriented agriculture to resilient, market-responsive, and environmentally sustainable livelihood systems. Ultimately, agricultural research strengthens not only crops and farms, but also rural communities and national food security. It builds the foundation for agricultural systems that can withstand shocks, adapt to change, and provide stable livelihoods while feeding a growing population.

Future Role of Agricultural Research

The coming decades will demand an entirely new vision for agricultural research—one that moves beyond incremental improvement and embraces transformation. Feeding a rapidly growing global population under tightening environmental constraints will require crops that are not only high-yielding, but also climate-proof, nutritionally enriched, and highly efficient in their use of water, nutrients, and energy. Future varieties must thrive under heat, drought, flooding, salinity, and emerging pest pressures, while maintaining productivity on shrinking and increasingly degraded farmland.

Advances in genomics, gene editing, artificial intelligence, robotics, and remote sensing will fundamentally reshape how crops are developed and how farms are managed. High-resolution genomic tools will allow researchers to decode complex traits such as drought tolerance, nutrient-use efficiency, and yield stability with unprecedented precision. Artificial intelligence and machine

learning will integrate massive datasets from genomics, phenotyping, weather, and soils to guide faster breeding decisions and predict field performance before crops are even planted. Robotics, sensors, and automation will transform field experimentation, crop monitoring, and precision input delivery, reducing labor demands while improving accuracy and efficiency. Future agricultural research will increasingly move away from studying isolated traits or technologies in isolation and toward a whole-systems approach. Genetics will be integrated with soil biology, agronomy, climate science, engineering, and socio-economics to design farming systems that are productive, resilient, and environmentally regenerative. Research will not only aim to improve crops, but also to redesign cropping systems that enhance biodiversity, rebuild soil health, conserve water, and reduce agriculture's ecological footprint. Equally important will be stronger and more inclusive collaboration among farmers, scientists, extension professionals, policymakers, and industry partners. Farmers will no longer be seen only as end-users of technology, but as co-innovators whose experiential knowledge helps guide research priorities and validate solutions. Policies and investment strategies will play a critical role in ensuring that innovations move rapidly from laboratories to landscapes, and that small and marginal farmers are not left behind.

The central goal of agricultural research will shift from maximizing yield alone to optimizing resilience, sustainability, profitability, and nutritional security. Future research will seek to deliver food systems that are not only productive, but also equitable, climate-adaptive, and environmentally responsible. Agricultural research will therefore not merely respond to global change it will actively shape the future of food, farming, and human well-being.

Conclusion

Agricultural research is not distant, abstract, or detached from reality. It is deeply practical, profoundly human, and fundamentally connected to the lives of farmers. It shapes the seeds they sow, the practices they follow, and the strategies they use to confront uncertainty. Behind every healthy crop and successful harvest lie years of invisible scientific effort, field experimentation, and collaborative learning.

By investing in agricultural research, societies invest in farmers, food security, and environmental sustainability. When research reaches the field, it does more than increase productivity. It builds resilience, strengthens livelihoods, and restores confidence in the future of farming. Ultimately, agricultural research does not merely grow crops—it nurtures hope, stability, and the foundations of human survival.

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INFO CROP: A DIGITAL ASSISTANT FOR INDIAN FARMERS**Dhanalakshmi V^{1*}, Manju P S², Chandru R³ and Manikandan N⁴**

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Abstract

Crop simulation models play a crucial role in understanding crop responses to environmental variability and management interventions. InfoCrop is a generic, process-based dynamic crop simulation model developed at the Indian Agricultural Research Institute (IARI) to simulate crop growth, development, yield and associated environmental processes. The model integrates weather conditions, soil characteristics, crop genotype, agronomic management, water and nitrogen dynamics and major pest stresses to provide a comprehensive assessment of crop performance under diverse agroecological situations. Since its introduction in 1997, InfoCrop has evolved through several versions with significant improvements in phenology, stress response mechanisms, soil carbon-nitrogen interactions and pest damage representation, enhancing its suitability for climate change impact studies and sustainable agriculture research. InfoCrop has been widely applied for climate risk assessment, optimization of water and nutrient use, crop management decision support and evaluation of emerging agricultural technologies. Despite certain limitations related to data intensity and parameter uncertainty, continuous model development and integration with advanced data sources are strengthening its role as an effective decision support tool for climate-resilient and sustainable agricultural systems.

Introduction

A model represents a simplified abstraction of reality, designed to describe and analyse real-world objects or systems. Crop simulation models are widely recognized as effective tools that use biophysical relationships to simulate crop growth and development, thereby supporting the assessment of productivity under different climatic conditions, management practices, and irrigation strategies at a substantially lower cost than field experimentation. InfoCrop is a generic, process-based dynamic crop simulation model developed by Aggarwal and his collaborators. In contrast to earlier models that addressed only selected components of crop growth, InfoCrop was developed as an integrated modelling framework capable of simulating crop growth and yield across a wide range of environmental conditions while incorporating the effects of agronomic management, water availability, nutrient dynamics, and pest stresses. The term "InfoCrop" reflects its role as an information-oriented tool for crop management, designed to generate practical insights that support the optimization of agricultural practices and enhance crop resilience to environmental stresses.

InfoCrop

InfoCrop is a crop model-based decision support system developed at the Indian Agricultural Research Institute (IARI). It is designed to simulate the combined effects of weather conditions, soil

properties, agronomic management practices, water and nitrogen availability, major pest stresses on crop growth, yield and greenhouse gas emissions. The overall framework of InfoCrop draws upon concepts and structures from several earlier crop models, incorporating the scientific expertise of the developers, particularly from models such as MACROS, SUCROS and WTGROWS. The system has been developed with a user-friendly interface to promote wider adoption of crop modelling in research and development, requiring relatively simple and readily accessible input data. Individual crop models within InfoCrop have been formulated by subject-matter specialists and validated across major crop-specific environments in India. In addition, the decision support system is supported by built-in databases of representative Indian soils, weather conditions and crop varieties, facilitating practical applications. InfoCrop currently includes simulation modules for major crops such as rice, wheat, maize, sorghum, pearl millet, potato, sugarcane, cotton, pigeonpea, chickpea, groundnut, mustard and soybean. The InfoCrop versions are InfoCrop 1.0 (1997), InfoCrop 1.1 (1999), InfoCrop 2.0 (2004), InfoCrop 3.0 (2011), InfoCrop 2.1 (2015).

Model inputs

Masters

In InfoCrop model, menu bar consists of various components such as masters, project, results, weather conversion etc. The Masters contain all the data available for selection in the project screen while carrying out a simulation. Some database for Indian crops, varieties, soils and weather, pest and organic matter have been given and the user can add similar data for own area of interest. When a simulation project is planned, it can be executed only for the database available in the Masters. Remember that the values in the database should be appropriate, in the desired units, and validated. The results of the simulation could be biased and even erroneous depending upon the database in Masters. New users are advised to check the Masters before starting the simulation projects. The Masters are divided into the following sub-modules:

a) Crop Master

This screen can be used to view or update the list of crops, which are included in InfoCrop. The user can simulate yields for crops present in Crop Master using the Project screen. The user can add a new crop to be analyzed using this screen, provided he has the validated crop model (crop.exe file name) and crop.dat files specific for that crop in the desired format. Most users cannot easily modify existing crop technical coefficients. However, if one has familiarity with the FST file structures and the model details then the specific crop.dat files can be edited. The crop name provided will be visible in the project for selection.

b) Variety Master

Variety Master is used to enter the crop variety details and its parameters. These parameters are so-called 'genotypic coefficients' that characterize the basic physiological behaviour of a variety. The Crop Variety parameters are categorized into three categories: phenology, growth, and source-sink balance. Measurement of these parameters is a very specialized job and may need experiments in controlled environments. Experience has shown that for most applications, once the correct phenology parameters have been set, simulation results are satisfactory. The specialists of various crops have built a database of key varieties in the Masters. These values are either through direct measurement or have been evolved through iterative calibration procedures.

c) Soil Texture Master

InfoCrop uses three soil layers for simulation. The thickness and other properties of each need to be specified. Soil texture master is a generic database of such soil properties based on texture. Soil

district master provides a database of soil properties has been provided for the dominant soil types of all districts of India based on literature survey and expert judgments. Soil district master can be used by the user to use this district-based soil texture data and associated properties. Please remember these are generalized properties of the soil in the selected district and may not sometimes meet user's expectations. In such cases user should input his own soil data before simulation.

d) Weather Master

InfoCrop needs "daily weather data (solar radiation (hrs), maximum and minimum temperatures (°C), rainfall (mm), wind speed (km/h) and vapour pressure (kPa))" in appropriate format for correct simulations. Weather master can be used by the user to provide details of weather data available in the project as well as to convert the data to InfoCrop formats. This contains a list of all the weather stations along with the weather data file containing details of daily weather data for different years, which could be included in the simulation. The model developers have already provided a minimum database. Users are required to add to this database the data of their respective weather stations.

The convention used for taking the weather data input files by the InfoCrop model includes the Station code, Station number and year in the following order: [station code + station number + "." + last three digits of year]. For example the file name for the station Delhi with station code 'DELH', station number '1' and year '1997' will be 'DELH1.997'. This weather data file must be present in the weatherdata folder of InfoCrop.

e) Pest Master

Pest Master can be used by the user to examine details of pests, their linkage with crops and the functions associated with this. This can also be used to add new pests, functions and associations. The list of pests provided here in the database is the one available in the project for selection as per the selected crop association.

f) Organic Matter Master

Organic Matter Master can be used by the user to provide details of different types of organic matter.

Calibration and validation of InfoCrop:

Like all simulation models, InfoCrop requires careful calibration and validation to ensure its predictions match real-world observations across different environments and management conditions.

The calibration process

Calibration involves adjusting model parameters to minimize the difference between simulated and observed values for key crop variables. This process typically follows a hierarchical approach:

1. Phenological calibration to accurately capture developmental timing
2. Growth calibration to match biomass accumulation patterns
3. Yield calibration to predict final harvested yield
4. Process-specific calibration for water use, nutrient uptake, or pest damage

For InfoCrop, calibration often focuses on crop-specific parameters like thermal time requirements, radiation use efficiency, and partitioning coefficients. The goal is to find parameter values that provide the best fit across multiple seasons and locations while remaining physiologically realistic.

Validation approaches

Validation tests whether a calibrated model can accurately predict crop performance under conditions different from those used during calibration. InfoCrop validation typically involves:

- **Independent dataset testing:** Using field data not involved in calibration
- **Multi-location validation:** Testing across different agroecological zones
- **Temporal validation:** Evaluating performance across different years and seasons
- **Management validation:** Testing under varying agricultural practices

Statistical metrics like root mean square error (RMSE), coefficient of determination (R^2), and agreement index are commonly used to quantify how well InfoCrop predictions match observed data.

Output and verifiable variables:

The standard output comprises dry weight of roots, stem, leaves, grain number and grain yield, leaf area index, N uptake by crop, soil water and N content, evapotranspiration, N and water stress.

Applications of the InfoCrop model

InfoCrop's versatility and comprehensive approach make it valuable for addressing various agricultural challenges:

Climate change impact assessment

InfoCrop has been extensively used to evaluate how climate change might affect crop production across different regions. By running simulations with projected future climate data, researchers can identify vulnerable crops and regions, quantify potential yield impacts, and explore the effectiveness of various adaptation strategies.

The model's ability to simulate both gradual climate trends and extreme weather events makes it particularly valuable for comprehensive climate risk assessment. Additionally, its greenhouse gas emission modules allow for analyzing both the impacts of climate change on agriculture and agriculture's contribution to climate change.

Resource use optimization

InfoCrop facilitates the efficient use of key agricultural inputs such as water, fertilizers, and energy by enabling the evaluation of alternative management strategies. The model supports the optimization of irrigation scheduling by identifying appropriate timing and application depths to improve water use efficiency, while also aiding fertilizer management through the assessment of suitable application rates and timings to enhance nutrient use efficiency and reduce losses. In addition, InfoCrop allows the analysis of trade-offs among different input combinations, helping to understand their effects on crop yield and environmental impacts. Through these capabilities, the model serves as a valuable tool for sustainable intensification, supporting increased food production while minimizing the use of environmental resources.

Crop management decision support

For farmers and extension services, InfoCrop offers practical support for making informed seasonal management decisions. The model can be used to identify optimal planting windows by analyzing climate forecasts, assist in selecting suitable crop varieties for specific local conditions, and evaluate the reliability of alternative management practices under variable weather scenarios. In addition, InfoCrop enables early-season yield forecasting, which supports advance planning and risk reduction in agricultural operations.

Technology evaluation

InfoCrop functions as a virtual experimentation platform for evaluating emerging agricultural technologies and management practices prior to their field application. The model enables

assessment of the potential performance of newly developed crop varieties across diverse environments, examination of the long-term impacts of conservation agriculture practices such as reduced tillage and residue retention, and testing of site-specific management strategies associated with precision agriculture. Through such simulations, InfoCrop helps identify and prioritize promising innovations for further research, development and field-level validation.

Limitations and future developments

Despite its wide applicability, InfoCrop has several limitations that should be considered by users. Owing to its comprehensive framework, the model requires detailed input data, which may not always be readily available and some simulated processes rely on parameters that are difficult to quantify accurately. In addition, uncertainty can arise when extrapolating point-based simulations to field or regional scales and certain complex processes may be simplified to maintain usability. To overcome these constraints, ongoing developments focus on integrating remote sensing data to improve model initialization and updating, incorporating machine learning approaches alongside process-based modeling, applying ensemble modeling techniques to minimize individual model biases and enhancing the user interface to improve accessibility for non-technical users.

Conclusion

The InfoCrop model represents a significant advancement in agricultural simulation technology, effectively bridging the gap between theoretical understanding of crop growth processes and their practical application by farmers, researchers, and policymakers. Its integrated framework, which combines crop development, soil processes, agronomic management practices, and environmental impacts, offers a comprehensive platform for analyzing complex agricultural systems. By enabling the evaluation of climate variability, resource use efficiency, and management strategies, InfoCrop supports informed decision-making aimed at enhancing productivity while ensuring environmental sustainability. Despite certain limitations related to data availability and parameter uncertainty, continuous improvements and emerging integrations with advanced technologies are strengthening its applicability. Overall, InfoCrop stands as a valuable decision support tool for promoting sustainable, climate-resilient, and resource-efficient agricultural production systems.

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