Open Access Multidisciplinary Online Magazine

# Agri-India TODAY

Monthly Magazine-cum-eNewsletter

ISSN : 2583-0910

Volume 06 | Issue 06 | June 2026

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ISSN : 2583-0910
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Peer reviewed
monthly newsletter

Article ID : 06/VI/01/0626

# INTEGRATING AI AND MACHINE LEARNING IN SOIL WATER ANALYSIS

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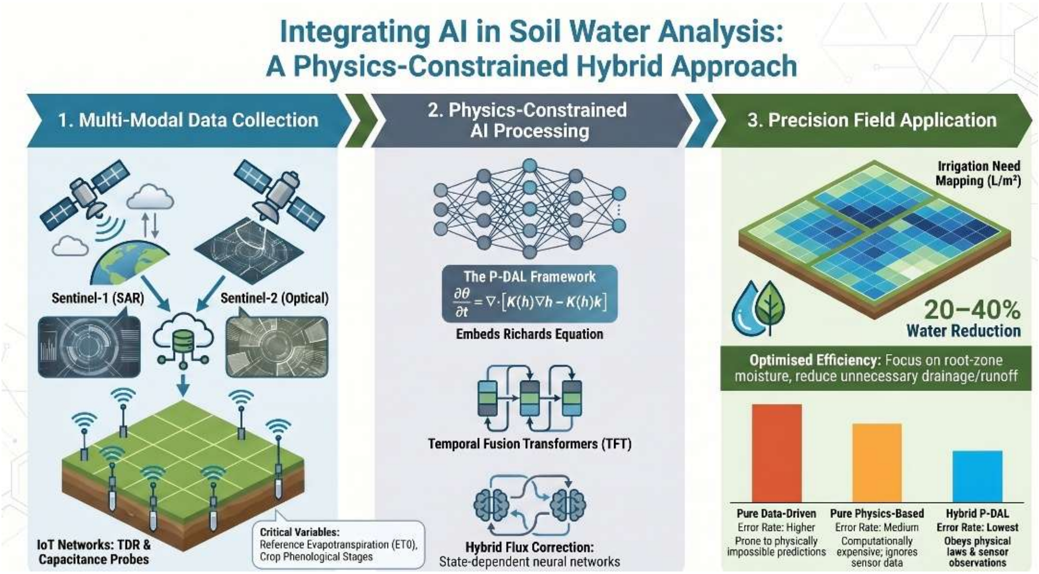
## The Shift from Measurement to Prediction

Traditional soil moisture analysis has mainly depended on two methods: precise but labour-intensive ground sensors like TDR probes, or broad satellite data such as SMAP, which has low resolution. These approaches often struggle with the "scale gap", either providing data that is too localised for large regions or too coarse for individual farms. The integration of AI and ML helps bridge this gap. Transitioning from solely physical measurements to predictive models allows us to accurately estimate soil moisture over large areas and at various depths (20, 40, and 80 cm), without requiring a sensor for every square meter.



## Key Machine Learning Architectures

Modern soil analysis employs various specialised algorithms, selected based on the data type:

### 1. Ensemble Learning (Random Forest & XGBoost)

Ensemble methods are the key tools for estimating soil moisture. They combine predictions from numerous models rather than relying on a single decision.

Random Forest (RF): Well-suited for capturing complex, non-linear relationships between soil texture and water content. It is highly resistant to noise in satellite data.

XGBoost & CatBoost: These gradient-boosting algorithms are currently leading in predictive performance for tabular data, often achieving $R^2$ scores above 0.85 in estimating root-zone moisture by analysing weather data such as precipitation and evapotranspiration.

### 2. Convolutional Neural Networks (CNN)

CNNs are mainly used for "Image-to-Moisture" analysis. They analyse spatial patterns in satellite images or drone photos to detect moisture stress. Unlike conventional methods, CNNs can "see" texture and color variations in soil that signal dryness much earlier than the human eye.

### 3. Recurrent Neural Networks (LSTM)

Since soil moisture is a time-dependent variable- with today's moisture influenced by previous rainfall- Long Short-Term Memory (LSTM) networks are crucial. They "remember" past moisture levels to forecast future conditions, making them essential for drought early-warning systems.

### Data Fusion: The Multi-Source Approach

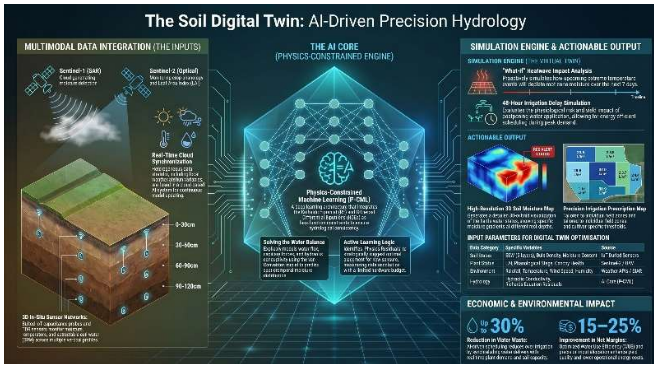
The impressive capabilities of artificial intelligence (AI) stem from its proficiency in processing and analyzing "Multi-Source Data." In the realm of soil analysis, a comprehensive AI framework is crafted by integrating four distinct yet interconnected data streams that enhance the accuracy and depth of insights.

1. **Remote Sensing**: This component primarily utilizes Synthetic Aperture Radar (SAR) data captured from Sentinel-1, which provides high-resolution images regardless of weather conditions or sunlight. Coupled with this is thermal data from the Landsat satellite, which aids in assessing surface temperatures. These remote sensing techniques allow for the monitoring of soil moisture levels, land cover changes, and overall landscape dynamics over large areas.
2. **Topographic Data:** Critical to understanding water movement and distribution, topographic data includes variables such as slope, elevation, and aspect. The slope of the land influences how quickly water can flow, while the elevation determines the potential for runoff or pooling in certain areas. The aspect, or the direction a slope faces, significantly impacts microclimates and can alter vegetation patterns, thereby affecting soil stability and moisture retention.
3. **Meteorological Data:** Real-time meteorological data encompasses measurements of temperature, humidity, wind speed, and precipitation. These factors are essential for understanding how climatic conditions influence soil moisture levels and crop health. By continuously monitoring these variables, the AI framework can respond to changes in weather patterns, predicting potential droughts or flooding events that may impact agricultural practices and soil management.
4. **Soil Properties:** This data stream focuses on the intrinsic characteristics of the soil, including the composition of clay, silt, and sand. The proportions of these elements define the soil's "holding capacity," which refers to its ability to retain moisture and nutrients. Understanding these properties is crucial for effective soil management and agricultural productivity, as they directly influence plant growth and ecosystem health.

Together, these data streams create a robust framework for soil analysis, enabling more informed decision-making in agriculture, environmental conservation, and land management. By leveraging the strengths of each data source, AI can uncover intricate relationships and patterns that may not be evident through single-source analysis alone.

## The Concept of the "Soil Digital Twin"

In 2026, a significant advancement in agricultural technology emerged in the form of the Soil Digital Twin. This innovative tool acts as a virtual, real-time simulation of a specific physical field, allowing farmers and agronomists to gain unprecedented insights into their crops and soil conditions. By harnessing the power of Internet of Things (IoT) sensors, which continuously collect data on various environmental factors, and combining this with advanced machine learning (ML) models, the Soil Digital Twin can conduct intricate "what-if" analyses.



For instance, it can assess scenarios such as:
- "What happens to the moisture levels in the soil if we delay irrigation by 48 hours?"
- "How does a heatwave impact the moisture levels in the root zone for this particular crop type?"

These simulations provide important insights that help users predict possible challenges and make well-informed decisions about crop management. A notable application of the Soil Digital Twin is in Precision Irrigation. This method optimizes water usage by delivering it only where and when it is required, greatly improving efficiency. According to reports, this targeted approach could decrease water waste by as much as 30%, making it a sustainable solution that is also financially advantageous for farmers.

## Challenges and the Path Forward

Despite advances, two significant challenges persist:

- The "Black Box" Issue: Many AI models deliver accurate results but lack explainability. Researchers are increasingly turning to Explainable AI (XAI) to help agronomists understand the reasoning behind specific moisture-level predictions.
- Limited Data Availability: In many developing areas, insufficient ground-truth data hampers the training of advanced models. Transfer Learning—a method where a model trained in one region is customised for another—is currently the best approach for these data-scarce environments.

## Conclusion

Integrating AI into soil water analysis shifts management from reactive to proactive. AI converts raw, complex environmental data into accurate maps and forecasts, enabling farmers to effectively manage the soil's "invisible reservoir" with greater precision. This approach helps secure food supply amid an unpredictable climate.

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ISSN : 2583-0910
**Agri-India TODAY**
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Peer reviewed
monthly newsletter

Article ID : 06/VI/02/0626

# INFORMATION AND COMMUNICATION TECHNOLOGY IN FISHERIES SECTOR

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## Abstract

Information and Communication Technology (ICT) is transforming the fisheries sector by improving productivity, efficiency, safety, and sustainability. Digital tools such as mobile phones, GPS, sensors, Artificial Intelligence, satellite systems, and online platforms support fisheries management, aquaculture, marketing, and governance. ICT helps in fish stock monitoring, weather forecasting, disease control, market access, and resource conservation. Despite challenges like poor connectivity, high costs, and low digital literacy, government initiatives and innovation are promoting wider adoption. Future trends such as smart fisheries, big data, and precision aquaculture will further modernize the sector and enhance livelihoods.

**Keywords**: ICT, Fisheries, Aquaculture, Sustainability, Artificial Intelligence, Digitalization.

## Inrroduction

Information and Communication Technology (ICT) refers to the use of digital tools such as computers, mobile phones, internet services, satellite systems, sensors, and communication networks for collecting, processing, storing, and sharing information. In the fisheries sector, ICT has become highly important for improving efficiency, productivity, and sustainability. Modern fisheries use ICT to provide weather forecasts, ocean condition updates, GPS navigation, fish market prices, and online advisory services to fishermen and fish farmers. Fisheries play a vital role in food security by supplying nutritious protein-rich food to millions of people worldwide. They also create employment opportunities in fishing, aquaculture, processing, transportation, and marketing, while contributing significantly to national income and exports. However, traditional fisheries face challenges such as overfishing, climate change, low productivity, and poor market access. Therefore, digital transformation is necessary to modernize the sector. ICT helps in resource management, disease control, traceability, e-commerce, and better decision-making, ensuring safer livelihoods and sustainable growth in fisheries.

## Concept of ICT in Fisheries

ICT in fisheries refers to the application of information and communication technologies in fisheries management, capture fisheries, and aquaculture for efficient operations and decision-making. It involves the use of digital tools to collect, store, process, analyze, and share important information related to fish production, water quality, weather, markets, and fish stock management. ICT helps fishermen, fish farmers, researchers, and government agencies improve productivity and sustainability. Common examples include mobile phones for communication, internet platforms for market updates, GPS for navigation, sensors for water monitoring, Artificial Intelligence (AI) for prediction and analysis, and satellite systems for weather and ocean data. ( Dash *et al.*, 2023).

## Importance of ICT in Fisheries

Information and Communication Technology (ICT) has become highly important in the fisheries sector by improving fish production and increasing overall productivity. Modern technologies such as mobile applications, water quality sensors, automated feeders, and farm management software help fish farmers monitor pond conditions, feeding schedules, fish health, and growth rates efficiently. These technologies reduce wastage of feed, save labor costs, and improve survival rates of fish. In capture fisheries, ICT tools such as GPS, sonar, and digital navigation systems help fishermen locate fishing zones accurately and save time and fuel. ICT also supports sustainable fisheries management by collecting real-time data on fish stocks, fishing effort, and environmental conditions. This information helps governments and fisheries authorities control overfishing, protect breeding grounds, and conserve aquatic biodiversity for future generations. (Omar *et al*., 2011).

ICT also provides timely weather forecasts, ocean condition updates, cyclone warnings, and emergency alerts, which improve safety for fishermen working at sea. Navigation systems help boats travel safely and return to shore during sudden weather changes. Post-harvest losses are reduced through better storage systems, cold chain monitoring, transportation tracking, and improved processing methods. ICT increases the income of fishers and fish farmers by giving access to current market prices, online fish markets, e-commerce platforms, and direct links with buyers, reducing the role of middlemen.

In addition, ICT strengthens communication among fishermen, traders, scientists, extension workers, and government agencies through mobile networks, websites, and social media platforms. It enables training, awareness programs, policy updates, and quick problem-solving. Therefore, ICT plays a major role in making fisheries more productive, profitable, safe, and environmentally sustainable in the modern world.

## Major ICT Tools Used in Fisheries

Communication technologies are essential in fisheries for sharing timely information among fishermen, fish farmers, traders, and government agencies. Mobile phones are the most widely used tool, helping fishers communicate with markets, family members, buyers, and extension officers. They are also used for accessing mobile applications related to weather forecasts, fish prices, and advisory services. SMS alerts are useful for sending quick updates such as cyclone warnings, heavy rainfall alerts, disease outbreaks, and government announcements. These messages reach users instantly, even in remote coastal areas. Social media platforms such as WhatsApp, Facebook, and YouTube help fishing communities exchange knowledge, training videos, market opportunities, and success stories. They also support online marketing of fish products. Radio and television remain important in many rural and coastal regions where internet access is limited. These media provide weather reports, educational programs, awareness campaigns, and news related to fisheries development.

Information technologies help in storing, processing, and managing fisheries data. Computers and databases are widely used by fisheries departments, hatcheries, and research institutions to maintain records of fish production, breeding, water quality, licenses, and sales. Proper databases improve planning and decision-making. Fisheries management software is used for farm planning, feed management, disease monitoring, inventory control, and financial management. It helps fish farmers operate efficiently and reduce costs. E-learning platforms are becoming popular for training fishers, students, and farmers through online courses, webinars, videos, and digital study materials. These platforms improve skills and technical knowledge.

Advanced ICT tools are transforming fisheries into a smart and modern sector. GPS and GIS mapping help fishermen identify fishing zones, navigate safely, and map aquatic resources. Remote sensing and satellite data provide information on sea surface temperature, chlorophyll concentration, and weather patterns, helping locate potential fishing areas. Internet of Things (IoT) sensors are used in aquaculture ponds to monitor water temperature, oxygen levels, pH, and water quality in real time. Artificial Intelligence (AI) supports disease detection, fish growth prediction, feeding optimization, and stock assessment. Drones are used for surveillance, pond inspection, and monitoring coastal areas. Blockchain technology improves traceability by recording each stage of fish production, processing, and transportation, ensuring food safety and transparency in trade. (Bosco, 2025).

## Applications of ICT in Fisheries

ICT has greatly improved capture fisheries by making fishing operations safer and more efficient. Fish shoal detection technologies such as sonar, echo sounders, and satellite-based systems help fishermen locate fish groups quickly, saving time and fuel. Navigation and route planning tools like GPS enable fishing vessels to travel accurately, identify productive fishing grounds, and return safely to shore. These systems also help avoid dangerous zones and reduce travel costs. Weather forecasting services provide real-time information on storms, wind speed, rainfall, tides, and sea conditions. This helps fishermen plan trips properly and avoid accidents at sea. Vessel monitoring systems (VMS) are used to track fishing boats, ensure safety, prevent illegal fishing, and support marine resource management. (Amuthakkannan *et al*., 2023).

In aquaculture, ICT supports better farm management and higher production. Water quality monitoring systems use sensors to measure temperature, pH, dissolved oxygen, and ammonia levels in ponds or tanks. This helps farmers maintain a healthy environment for fish growth. Automatic feeding systems provide feed at the right time and quantity, reducing waste and improving feed efficiency. Disease detection and control technologies use cameras, sensors, and AI-based tools to identify fish diseases early, allowing quick treatment and reducing losses. Farm management apps help farmers maintain records of stocking, feeding, medicine use, harvest schedules, and expenses.

ICT improves fish marketing and trade through online fish marketplaces, where farmers and fishers can directly sell products to consumers or traders. Price information systems provide daily market prices, helping sellers choose the best market and increase profits. Supply chain management software tracks movement of fish products from farm to market. Cold chain monitoring systems maintain proper storage temperatures during transport, reducing spoilage and preserving quality.

ICT is also valuable for fisheries governance. Licensing and registration systems simplify issuing permits and maintaining records of fishers and boats. Fish stock assessment uses digital data to estimate fish populations and support conservation. Data collection and analysis improve planning and decision-making. ICT also supports policy planning by providing accurate information for sustainable fisheries development.

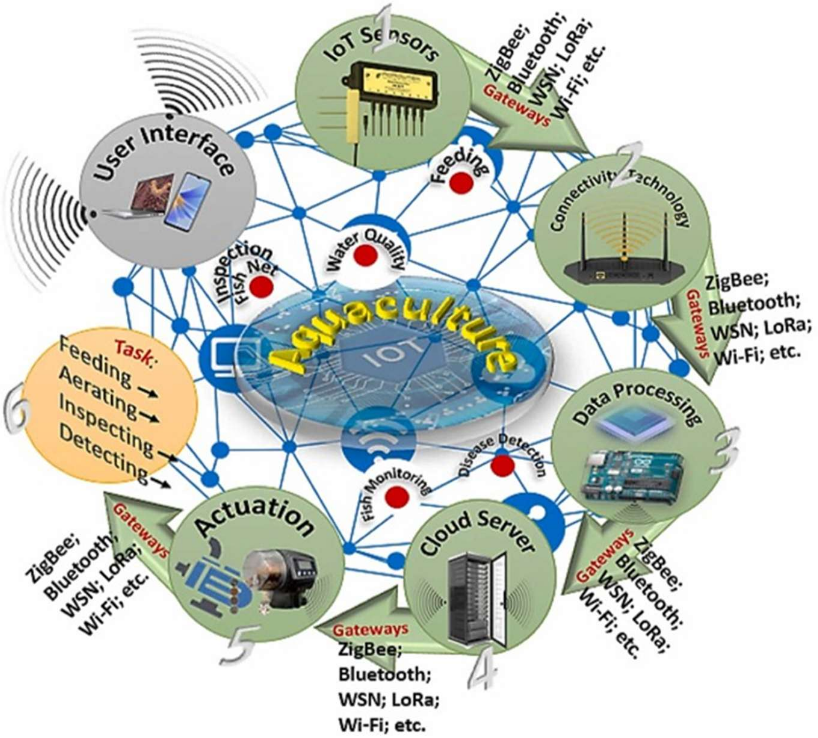

Fig: Applications of ICT in Fisheries MDPI, *AgriEng.* (2025)

**Benefits of ICT in Fisheries**

Information and Communication Technology (ICT) provides many benefits to the fisheries sector by improving productivity, management, and livelihoods. One major benefit is higher efficiency, as digital tools such as sensors, GPS, mobile apps, and automated systems help fishermen and fish farmers perform tasks faster and more accurately. ICT also leads to cost reduction by saving fuel, labor, feed, and time through better route planning, precise feeding, and efficient resource use.

Another important advantage is better decision-making. Real-time data on weather, water quality, fish growth, and market prices helps fishers, farmers, and managers make informed choices. ICT also ensures increased safety at sea by providing weather forecasts, cyclone warnings, emergency alerts, and navigation support, reducing risks for fishermen.

ICT promotes transparency in trade by improving record-keeping, online transactions, and traceability systems such as blockchain, which help build consumer trust and reduce fraud. It also supports better resource conservation through monitoring fish stocks, preventing illegal fishing, and promoting sustainable harvesting practices.

Most importantly, ICT contributes to improved livelihoods of fishing communities by increasing income, creating employment opportunities, expanding market access, and providing training and knowledge services. Thus, ICT plays a key role in making fisheries more profitable, safe, and sustainable.

**Challenges in ICT Adoption**

Despite its many benefits, the adoption of ICT in fisheries faces several challenges. One major problem is poor internet connectivity in coastal and rural areas, which limits access to online services, weather updates, and digital marketplaces. The high cost of devices and infrastructure, such as smartphones, sensors, computers, and network systems, makes adoption difficult for small-scale fishers and farmers.

Another challenge is the lack of digital literacy, as many users are unfamiliar with modern technologies and online platforms. This is further affected by limited training and awareness programs in remote communities. Language barriers also create difficulties when apps and services are available only in major languages instead of local languages. There are also concerns about data privacy and cybersecurity, as users may fear misuse of personal or business information. Finally, some fishers and farmers show resistance to new technology due to traditional practices, lack of trust, or fear of failure. Overcoming these challenges is essential for successful ICT adoption in fisheries. (Sabu *et al*., 2018).

### Government and Institutional Initiatives

Governments and institutions play an important role in promoting ICT in fisheries through various development programs and support services. Digital fisheries programs are introduced to modernize the sector by using online systems for data management, fish production monitoring, resource mapping, and market linkages. These programs help improve efficiency and transparency in fisheries administration. Mobile advisory services provide fishermen and fish farmers with timely information on weather forecasts, disease control, feeding practices, market prices, and government schemes through SMS, mobile apps, and helplines. This helps users make better decisions and increase productivity.

E-governance portals simplify services such as licensing, registration, subsidy applications, insurance claims, and scheme benefits through online platforms. These systems save time and reduce paperwork. Training programs organized by fisheries departments, universities, NGOs, and international agencies help fishers and farmers learn digital skills, modern technologies, and sustainable fisheries practices. Such initiatives encourage wider adoption of ICT and strengthen fisheries development.

### Future Trends in ICT in Fisheries

The future of fisheries is closely linked with advanced Information and Communication Technology (ICT), which will make the sector smarter, more productive, and sustainable. Smart fisheries will use connected devices, sensors, and digital platforms to monitor fishing activities, fish stocks, and environmental conditions in real time. This will improve management and reduce overexploitation of aquatic resources.

AI-based stock prediction is an emerging trend where Artificial Intelligence analyzes past data, weather patterns, ocean temperature, and fish movement to predict fish availability. This helps fishermen plan better fishing operations and supports sustainable harvesting. (Dash *et al*., 2023).

Smart aquaculture systems will become more common, using sensors and automation to control water quality, feeding schedules, disease detection, and fish growth. These systems reduce labor costs and increase production efficiency. Big data analytics will process large volumes of fisheries data collected from farms, markets, satellites, and vessels, helping governments and businesses make better decisions.

Cloud computing will allow fisheries data to be stored online and accessed from anywhere. Farmers, researchers, and officials can share information quickly and securely through cloud platforms.

Autonomous vessels or unmanned fishing boats may be used in the future for monitoring, surveillance, and fishing operations with reduced human risk.

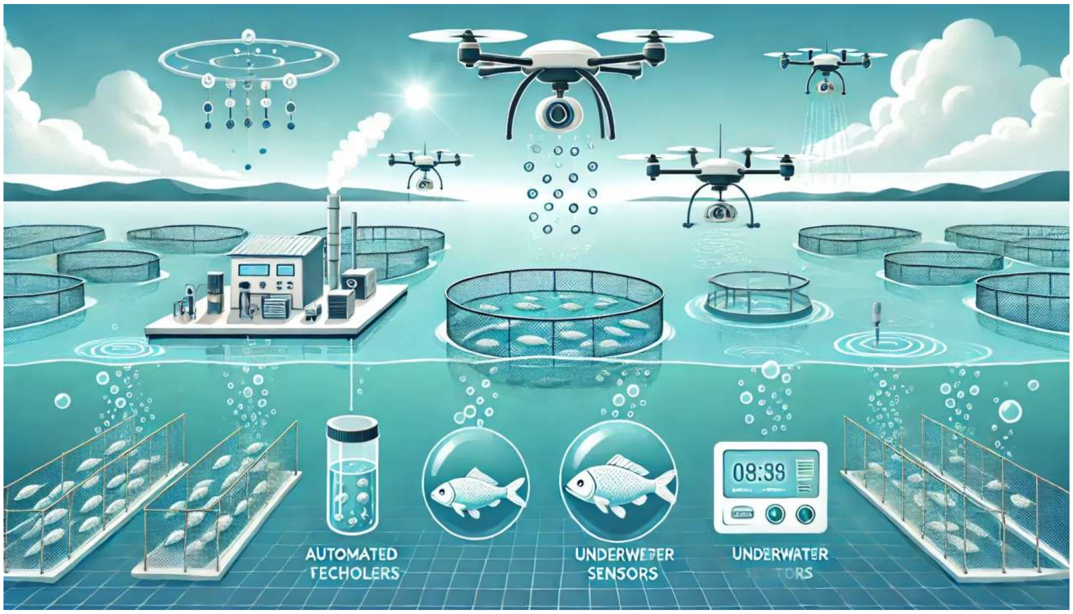

Fig: Future Trends in ICT in Fisheries (Naomi A, 2021)

Another important trend is precision aquaculture, where digital technologies provide exact control over feeding, water quality, medicine use, and stocking density. This improves fish health and minimizes waste. Overall, future ICT trends will transform fisheries into a modern, efficient, profitable, and environmentally friendly sector.

## Recommendations

To increase the adoption of Information and Communication Technology (ICT) in fisheries, several practical steps are necessary. First, governments should improve rural and coastal connectivity by expanding internet networks, mobile coverage, and digital infrastructure in remote fishing areas. Better connectivity will help fishers access weather updates, market prices, and advisory services in real time. Second, regular training programs should be provided to fishers and farmers so they can learn to use mobile apps, GPS devices, sensors, and online platforms effectively. Digital literacy is essential for successful ICT adoption. Training can be organized through fisheries departments, universities, and extension agencies. Third, authorities should subsidize digital tools such as smartphones, water quality sensors, GPS devices, and farm management software. Financial support will help small-scale fishers and fish farmers adopt modern technologies at affordable costs.

Another important recommendation is to promote local language apps and user-friendly platforms so that rural communities can easily understand and use ICT services. Information in local languages increases participation and awareness. Governments should also strengthen public-private partnerships by involving technology companies, cooperatives, research institutions, and NGOs in fisheries development projects. Such collaboration can improve innovation, infrastructure, and service delivery.

Finally, there should be greater support to encourage research and innovation in smart fisheries, disease control systems, AI tools, and sustainable aquaculture technologies. Continuous research will help solve emerging challenges and improve productivity. Overall, these recommendations can make fisheries more modern, profitable, and sustainable through effective ICT use.

## Conclusion

Information and Communication Technology (ICT) is playing a transformative role in the fisheries sector by making it smarter, safer, and more sustainable. Through the use of digital tools such as mobile phones, GPS, sensors, Artificial Intelligence, satellite systems, and online platforms, fisheries operations have become more efficient and productive. ICT helps fishermen and fish farmers improve fish production, reduce costs, access market information, and make better decisions based on real-time data. It also enhances safety by providing weather forecasts, navigation support, and emergency alerts for those working at sea. Proper adoption of ICT can significantly increase productivity, income, and environmental protection. Technologies for water quality monitoring, stock assessment, disease control, and traceability help conserve aquatic resources and promote responsible fishing practices. Better market access and digital trade systems improve the livelihoods of fishing communities. The future development of fisheries depends greatly on continuous digital innovation. Emerging technologies such as smart fisheries, big data analytics, cloud computing, autonomous vessels, and precision aquaculture will further modernize the sector. Therefore, investment in infrastructure, training, research, and policy support is essential to fully realize the benefits of ICT and ensure long-term growth and sustainability in fisheries.

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ISSN : 2583-0910
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monthly newsletter

Article ID : 06/VI/03/0626

# CLIMATE-RESILIENT AGRICULTURE IN INDIA: A REMOTE SENSING PERSPECTIVE

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## Abstract

Climate change is significantly affecting Indian agriculture through rising temperatures, erratic rainfall, and increasing extreme weather events. India's large rainfed farming system (≈52% of cultivated land) is particularly vulnerable to monsoon variability (IPCC, 2023). Recent studies indicate that climate variability accounts for nearly 30–40% of crop yield fluctuations (Lobell *et al.*, 2011). Heat stress, droughts, and floods are reducing crop productivity and increasing production instability. Remote Sensing (RS) and Geographic Information Systems (GIS), integrated with Artificial Intelligence (AI), provide powerful tools for real-time crop monitoring, drought assessment, and yield prediction. Technologies such as NDVI enable early detection of crop stress and support climate-resilient decision-making. This article highlights recent (2020–2026) climate trends, their impacts on Indian agriculture, and the role of geospatial technologies in improving resilience and sustainability (ISRO 2022).

**Keywords:** Climate change, Remote sensing, GIS, NDVI, Agriculture

## Introduction

Agriculture in India is highly sensitive to climatic parameters such as temperature, rainfall, and solar radiation. Climate change, driven by anthropogenic greenhouse gas emissions, is altering these parameters and increasing climatic variability. India's agriculture supports nearly half of the population and remains largely dependent on monsoon rainfall, with about 52% of cultivated land being rainfed. Recent scientific studies indicate that climate variability is already impacting crop productivity and stability (Ray e*t al.*, 2013). Rising temperatures, irregular rainfall, and frequent extreme weather events are emerging as major threats to food security. In this context, Remote Sensing (RS) and Geographic Information Systems (GIS) are playing a crucial role in monitoring climate impacts and supporting adaptive agricultural practices (WMO 2025).

## Climate change Trends

India has experienced a significant rise in temperature, with an increase of about 0.8–0.9°C since the early 20th century, as highlighted by the Intergovernmental Panel on Climate Change (IPCC AR6, 2023)**.** Recent decades show accelerated warming, especially in northwest India, leading to more frequent and intense heatwaves. These extreme heat events are becoming longer and more widespread, posing serious risks to agriculture, water resources, and human health (IPCC, 2023; WMO, 2025).

## Monsoon Trends

The Indian monsoon is becoming increasingly erratic due to climate change. While some regions show a decline in average rainfall, there is a clear rise in extreme rainfall events**,** resulting in floods and dry spells occurring in the same season. This reflects the intensification of the hydrological cycle under warming conditions, disrupting cropping patterns and increasing vulnerability of rainfed agriculture (IPCC, 2023; WMO, 2025).

**Extreme Weather Events**

India is witnessing a sharp increase in extreme weather events such as heatwaves, floods, cyclones, and droughts**,** now occurring almost throughout the year. Ocean warming in the Indian Ocean is intensifying cyclones, while changing atmospheric conditions are increasing disaster frequency. These events are already impacting agriculture and livelihoods, confirming that India has become a climate-risk hotspot requiring urgent adaptation strategies (IPCC, 2023; Government of India, 2023).

**Temperature & Heat Stress Impacts**

Rising temperatures are significantly reducing crop productivity in India, particularly during sensitive growth stages. Studies aligned with the Intergovernmental Panel on Climate Change (IPCC AR6, 2023) indicate that even small increases in temperature can sharply reduce yields. For example, wheat yields in the Indo-Gangetic Plains are projected to decline by 1–8% due to temperature rise alone and up to 36% when combined with water stress (Lobell *et al*., 2011). Long-term projections also show that rice yields could decline by up to 22% under high-emission scenarios. Heat stress further increases evapotranspiration, leading to higher irrigation demand and reduced water-use efficiency.

### Impact of climate change on agriculture

**Monsoon Variability & Water Stress Impacts**

Climate change is intensifying rainfall variability, directly affecting agricultural stability. Research indicates that by 2050, paddy yields may decline by ~24%**,** while wheat yields could fall by 6–7% in the Indo-Gangetic Plains under moderate climate scenarios. Erratic monsoon patterns such as delayed onset and uneven distribution lead to both droughts and floods within the same season. Since over 50% of India’s population depends on agriculture**,** and a large share of farming is rainfed, this variability significantly threatens food security and farmer livelihoods.

**Extreme Events, Pests & Soil Impacts**

The increasing frequency of extreme events such as heatwaves, floods, and cyclones is causing substantial crop losses and economic damage. Studies suggest that climate change could lead to yield losses exceeding 25–30% for major crops by the end of the century under high-emission scenarios. Additionally, about 60% of farmers report increased pest and disease incidence due to changing climatic conditions, further reducing productivity (Government of India, 2023). Soil degradation is also accelerating, with rising temperatures and erratic rainfall contributing to loss of soil organic carbon, salinity, and reduced fertility (Lal 2015). Together, these impacts are increasing yield variability and making Indian agriculture more vulnerable to climate risks.

### Role of Remote Sensing and GIS

**Crop Monitoring (NDVI)**

Remote sensing indices like NDVI enable large-scale monitoring of crop health and stress (ISRO 2022). Studies show >80% of India’s agricultural areas have positive NDVI trends**,** while sudden declines help detect early stress and support yield forecasting (Indian Space Research Organisation;IPCC,2023**)**.

**Fig. 1. Crop Monitoring**

**Drought & Flood Monitoring**

GIS and satellite data provide near real-time assessment of soil moisture, rainfall, and crop conditions. Flood mapping using SAR imagery has shown that ~9.5 million ha of cropland were affected in 2025, enabling early warning and contingency planning (FAO, 2022).

**Precision & AI-based Agriculture**

Remote sensing integrated with GIS and AI supports precision farming through site-specific input use. These technologies can improve input efficiency by 15–25% and enable early yield and pest forecasting, making agriculture more climate-resilient (IPCC, 2023; ICAR, 2023).

| Strategy Area | Key Practices | Adaptation Benefits | Mitigation Benefits | Source |
|---|---|---|---|---|
| Climate-Resilient Crops | Heat- & drought-tolerant varieties, millets, short-duration crops | Reduce yield loss by 10–30% under stress | Efficient resource use | IPCC (2023); ICAR (2023) |
| Water Management | Drip irrigation, rainwater harvesting, AWD in rice | Saves 30–50% water, stabilizes yields | AWD reduces ~30% $CH_4$ emissions | FAO (2022); IPCC (2023) |
| Soil & Cropping Practices | Zero tillage, residue retention, crop diversification | Improves soil moisture & resilience | Increases soil carbon, reduces burning (~40–50%) | Lal (2015); ICAR |
| Risk Management | Agro-advisories, early warning systems, crop insurance (PMFBY) | Reduces climate risk & economic losses | Promotes sustainable practices | Government of India (2023) |
| Agroforestry & Precision Farming | Tree-based systems, site-specific nutrient management | Enhances farm stability & microclimate | Sequesters 2–4 t $CO_2$/ha/year | FAO (2022); IPCC (2023) |

**Fig. 2. Agroforestry & Precision Farming**

## Conclusion

India's agriculture is increasingly vulnerable to climate change, with rising temperatures and erratic rainfall reducing yields and increasing production variability. Evidence from IPCC and national assessments indicates an accelerating trend of climate risks. Geospatial technologies (RS/GIS), integrated with AI, enable real-time crop monitoring (e.g., NDVI), early warning of droughts and floods, and precision-based decision-making. Transitioning from reactive to predictive agriculture will require climate-smart practices, improved crop varieties, efficient water management, and risk mitigation tools such as insurance and advisories. Sustainable approaches, including conservation agriculture and agroforestry, further enhance resilience through soil carbon improvement. A combined strategy of technological innovation and sustainable agronomy is essential to ensure long-term food security under changing climatic conditions.

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ISSN : 2583-0910
Agri-India TODAY
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Peer reviewed
monthly newsletter

Article ID : 06/VI/04/0626

# SPATIOTEMPORAL MAPPING OF HARMFUL ALGAL BLOOMS USING MULTI-SOURCE REMOTE SENSING DATA

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## Abstract

Harmful algal blooms (HABs) are increasingly threatening marine ecosystems, fisheries, aquaculture, and human health, driven by nutrient enrichment, coastal urbanization, and climate change. This study examines the role of satellite remote sensing and GIS in monitoring and mapping HABs across marine systems. Ocean colour sensors including MODIS, Sentinel-3 OLCI, and VIIRS enable large-scale detection of chlorophyll-a concentrations, sea surface temperature anomalies, and turbidity, serving as key indicators of bloom formation and intensity. GIS integration supports spatial mapping of bloom hotspots, temporal analysis of seasonal variability, and development of early warning systems for coastal managers and fisheries stakeholders. Environmental drivers including nutrient runoff, warming temperatures, and altered ocean circulation are assessed in relation to bloom dynamics. Recent advances in machine learning, hyperspectral imaging, and cloud computing platforms such as Google Earth Engine are further enhancing HAB classification, forecasting, and real-time monitoring capabilities. Strengthening these geospatial approaches is essential for mitigating HAB impacts and supporting sustainable marine resource management.

**Keywords:** Harmful Algal Blooms, Satellite Remote Sensing, GIS, Chlorophyll-a, Sea Surface Temperature, Ocean Colour Sensors, Early Warning Systems

## Introduction

Harmful algal blooms (HABs) are rapid proliferations of phytoplankton species that negatively impact marine ecosystems, fisheries, aquaculture, and human health. Some HAB species produce toxins that contaminate seafood, while others deplete dissolved oxygen and create hypoxic conditions harmful to marine organisms. In recent decades, the frequency, intensity, and geographic distribution of HABs have increased globally due to nutrient enrichment, coastal urbanization, and climate driven ocean changes (Berdalet *et al.*, 2020).

Marine ecosystems are highly sensitive to environmental variability, making continuous monitoring of HABs essential for sustainable resource management. Traditional field-based monitoring methods are often expensive, time consuming, and spatially limited. In contrast, satellite remote sensing offers a cost-effective and large-scale approach for monitoring HAB dynamics in near real time (Mouw *et al.*, 2019).

## Satellite Remote Sensing for HAB Monitoring

Satellite remote sensing has become a major tool for HAB detection because it provides repeated observations over extensive oceanic and coastal regions. With the advantages of large-scale, real-time, and long-term monitoring, satellite remote sensing has been widely used to detect HABs as well as the oceanographic environmental characteristics that favour the formation of HABs. Ocean colour sensors measure the spectral reflectance of water surfaces and estimate biological and physical properties associated with algal blooms. The most successful methods for HAB detection have used spectrally derived products such as chlorophyll-a (Chl-a) estimates, as phytoplankton increases the backscattered light within pigment absorption spectral frequencies. Sensors such as MODIS, Sentinel-3 OLCI, and VIIRS are widely used for HAB detection and chlorophyll-a estimation (Tilstone *et al.*, 2021). Chlorophyll-a concentration is commonly used as an indicator of phytoplankton biomass, allowing scientists to identify bloom formation and monitor bloom intensity.

Remote sensing with satellites has become a powerful tool to monitor parameters such as sea surface temperature, turbidity, and chlorophyll-a levels, enabling ocean warming and harmful algal blooms to be tracked over large regions. Remote sensing also enables detection of sea surface temperature anomalies, turbidity, colored dissolved organic matter, and fluorescence signals that are often associated with HAB events. Oceanographic parameters such as chlorophyll-a and SST derived from satellite data normally serve as effective indicators for HABs; however, in turbid coastal waters, complex optical signals contributed by CDOM and particulate inorganic materials complicate reliable HAB detection.

A potential synthesized framework established by combining multiple satellite remote sensing approaches including spectral analysis, parameter retrieval, and spatial-temporal pattern analysis aims to lead to systematic and comprehensive monitoring of HABs from multiple oceanographic perspectives, thereby improving bloom detection accuracy and reducing misclassification between harmful and non-harmful blooms (Shen and Guo, 2012). Recent advances in hyperspectral satellite technology have further enhanced species discrimination by detecting subtle pigment differences among phytoplankton groups. These developments are particularly useful for identifying toxin-producing dinoflagellates, cyanobacteria, and diatoms (Arias *et al.*, 2025).

## GIS Applications in HAB Mapping and Analysis

Geographic Information Systems (GIS) play a crucial role in processing, integrating, and visualizing HAB-related datasets. GIS combines satellite observations with oceanographic and environmental parameters such as sea surface temperature, salinity, nutrient concentration, wind speed, and ocean currents. This integration supports spatial mapping of bloom hotspots and helps identify regions highly vulnerable to recurrent HAB outbreaks. GIS-based temporal analysis also enables researchers to study seasonal variability, bloom persistence, and long-term changes in bloom distribution (Anderson *et al.*, 2019).

Spatial interpolation and overlay analysis are commonly used to examine relationships between HAB occurrence and environmental drivers. In fisheries management, GIS-generated HAB risk maps are useful for identifying vulnerable aquaculture zones, shellfish harvesting areas, and fishing grounds. GIS also supports decision-making by enabling early warning systems, where bloom predictions can be disseminated to coastal managers, fishers, and public health agencies.

## Environmental Drivers of HABs

HAB occurrence is influenced by a combination of physical, chemical, and biological factors. Nutrient enrichment from agricultural runoff, wastewater discharge, and industrial pollution is a major driver of bloom development in coastal waters. Climate change is intensifying HAB risk by increasing sea surface temperature, enhancing water column stratification, and altering precipitation and runoff patterns. Warmer ocean temperatures can promote faster phytoplankton growth and extend bloom duration in many regions (Berdalet *et al.*, 2020). Ocean circulation patterns, upwelling intensity, and wind-driven transport also affect bloom initiation and dispersal. Therefore, integrating remote sensing with oceanographic models improves understanding of HAB mechanisms and spatial variability.

**Impacts of HABs on Marine Systems and Fisheries**

HABs can cause severe ecological and economic losses. HABs can harm humans and animals through their toxicity or by producing ecological conditions such as oxygen depletion, which can kill fish and other economically or ecologically important organisms; moreover, HAB outbreaks can lead to the closure of fisheries, aquaculture, and recreational areas, causing declines in businesses, tourism, and associated services (Oh *et al.*, 2023). Dense blooms can disrupt ecosystems by reducing light penetration contributing, for example, to seagrass decline and by depleting oxygen during decay, often leading to mass mortalities (Chiappi *et al.*, 2025). Eutrophication driven by HABs disrupts the natural balance of aquatic ecosystems by increasing turbidity levels and reducing light penetration and dissolved oxygen, thereby compromising water quality and biodiversity, with impacts extending to aquaculture, drinking water supplies, and water recreation (Newton and Melaram., 2023).

The five most commonly recognized HAB-related illnesses are diarrhetic shellfish poisoning (DSP), paralytic shellfish poisoning (PSP), amnesic shellfish poisoning (ASP), neurotoxic shellfish poisoning (NSP), and ciguatera poisoning (CP); humans are exposed to these toxins mainly through the consumption of fish and shellfish, which serve as the main biological vectors, and the risk of human diseases linked to toxigenic HABs is on the rise, corresponding to a dramatic increase in the occurrence, frequency, and intensity of toxigenic HABs in coastal regions worldwide (Yuan *et al.*, 2024). The phytoplankton species mostly involved in these toxic events are dinoflagellates or diatoms belonging to the genera Alexandrium, Gymnodinium, Dinophysis, and Pseudo-nitzschia, and substantial economic losses ensue after HAB occurrence, with sectors mainly affected including commercial fisheries, tourism, recreational activities, and public health monitoring and management (Farabegoli *et al.*, 2018). Fisheries and aquaculture sectors are particularly vulnerable to HAB outbreaks. HAB events often result in fish mortality, reduced aquaculture productivity, fisheries closures, and trade restrictions. These impacts can significantly affect coastal economies dependent on marine resources.

**Recent Technological Advances**

The integration of machine learning and artificial intelligence with satellite data is improving HAB classification and forecasting. Algorithms such as random forests, neural networks, and support vector machines are increasingly used to detect bloom patterns and predict outbreak probability (Torbick *et al.*, 2023). Cloud computing platforms such as Google Earth Engine have also facilitated large-scale analysis of satellite data, enabling faster processing of HAB datasets. These innovations support near real-time monitoring and improve operational HAB forecasting systems. Future satellite missions with higher spatial, temporal, and spectral resolution are expected to further improve HAB detection capabilities and support global marine monitoring programs.

**Conclusion**

Satellite remote sensing and GIS have become indispensable tools for mapping and monitoring harmful algal blooms in marine systems. Their integration provides efficient, large-scale, and timely assessment of bloom occurrence, environmental drivers, and ecological impacts.

With increasing HAB frequency under climate change, advanced geospatial technologies will remain essential for early warning, fisheries management, coastal planning, and marine ecosystem conservation. Continued improvements in hyperspectral imaging, machine learning, and data integration are expected to strengthen HAB monitoring and predictive capabilities in the future.

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ISSN : 2583-0910
Agri-India TODAY
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Peer reviewed
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Article ID : 06/VI/05/0626

# EMERGING CONTAMINANTS IN AQUATIC ENVIRONMENTS: A GROWING CONCERN

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## Introduction

When we think of ocean and river pollution, our minds usually drift to dramatic images: turtles tangled in six-pack rings, oil-slicked shorelines, or floating islands of plastic bottles. But there is a more insidious threat lurking beneath the surface—one we cannot always see, smell, or touch. Meet the "Emerging Contaminants." These are not your grandfather’s industrial pollutants. They are the trace remains of our modern lifestyle: the caffeine from your morning coffee, the estrogen from birth control pills, the UV filters from your sunscreen, and the tiny microfibers shedding from your yoga pants. While these contaminants have likely been present for decades, our ability to detect them has only recently caught up. And what scientists are finding is alarming. These substances are turning up in every drop of water on Earth—from the deepest ocean trenches to remote mountain streams. Because they are not necessarily removed by standard sewage treatment, they continuously flow into our aquatic environments, creating a "cocktail" of chemicals whose long-term effects we are just beginning to understand.

**Keywords**

- Micropollutants
- Endocrine Disrupting Compounds (EDCs)
- Per-and polyfluoroalkyl substances (PFAS / "Forever Chemicals")
- Microplastics & Nano-plastics
- Pharmaceutical residue
- Bioaccumulation

## Which Types of Emerging Contaminants Affect Aquatic Environments?

Not all contaminants are created equal. Here are the main "invisible" villains currently stressing our oceans, rivers, and estuaries:

1. **Pharmaceuticals and Personal Care Products (PPCPs):** This includes antibiotics, antidepressants, painkillers (like ibuprofen), fragrances, and antiseptics (like triclosan). They enter the water via human excretion and shower drains.
2. **Endocrine Disrupting Chemicals (EDCs):** Found in pesticides, industrial solvents, and plastics (like BPA). Even at concentrations measured in parts per trillion, these chemicals can mimic or block natural hormones.
3. **Per- and Polyfluoroalkyl Substances (PFAS):** Dubbed "forever chemicals" because they do not degrade naturally. Used in non-stick pans, waterproof jackets, and firefighting foam.

4. **Microplastics (& Nanoplastics):** Tiny fragments resulting from the breakdown of larger plastic items or microbeads from cosmetics.
5. **Synthetic Fertilizers & Road Salts:** While less "sexy" than drugs, excess nitrogen, phosphorus, and chloride disrupt the basic chemistry of fresh and coastal waters.

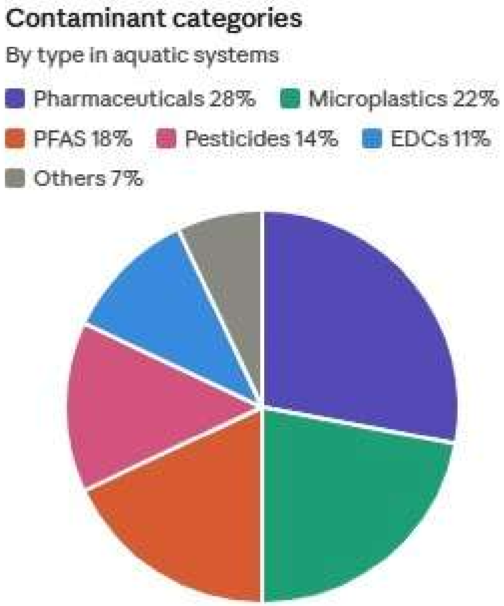

Fig:1 Emerging Contaminants Affect Aquatic Environments

**How These Contaminants Alter Biological & Physical Oceanographic Parameters**

The ocean is a living, breathing machine. Emerging contaminants are throwing a wrench into the gears, affecting both the biology (living things) and physics (water properties/currents) of the sea.

**Biological Impacts (The Living Ocean)**

- **Sex Change in Fish:** This is the horror story of aquatic toxicology. Exposure to EDCs (from birth control pills and plastics) causes male fish to develop female reproductive tissues. In some rivers downstream of treatment plants, populations of fathead minnows have collapsed because the fish literally cannot reproduce.
- **Antibiotic Resistance:** When rivers receive wastewater full of antibiotics, bacteria in the sediment evolve to become "superbugs." These resistant genes can travel across oceans, threatening human medicine.
- **Altered Behavior:** Antidepressants like fluoxetine (Prozac) are surprisingly stable in water. Studies show that shrimps and crabs exposed to these levels become bolder, leaving shelter more often and getting eaten by predators at three times the normal rate.
- **Phytoplankton Disruption:** These microscopic algae produce 50% of the oxygen on Earth. Certain contaminants (like herbicides and nanoparticle metals) inhibit their photosynthesis, potentially weakening the very base of the marine food web.

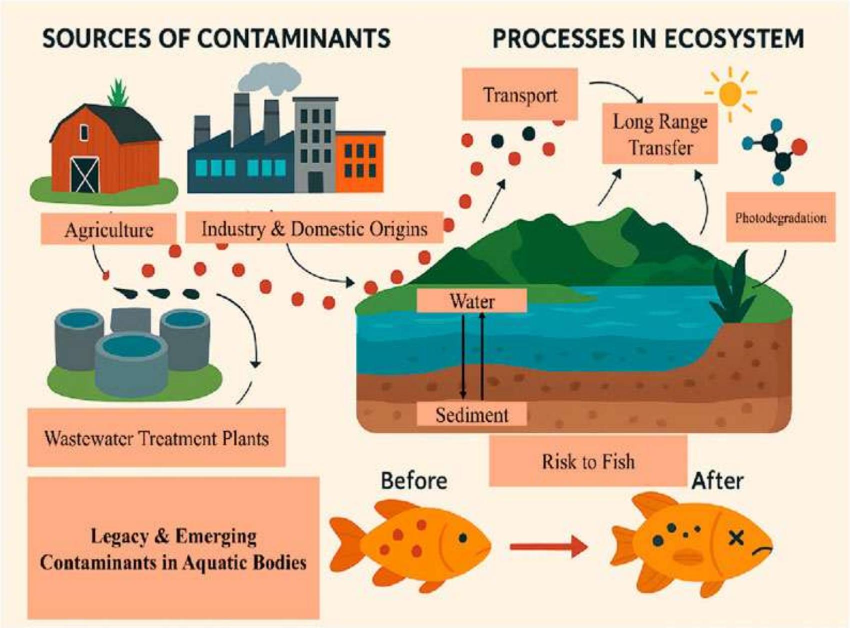

Fig:2 Pathways and Effects of Legacy and Emerging Contaminants in Aquatic Ecosystems

**Physical Oceanographic Impacts**

- **Increased Water Stratification:** Excess freshwater contaminants (like road salts and fertilizer runoff) change water density. This creates stronger "layers" (stratification) in estuaries. When layers don't mix, deep oxygen cannot be replenished, leading to massive "Dead Zones" where nothing can live.

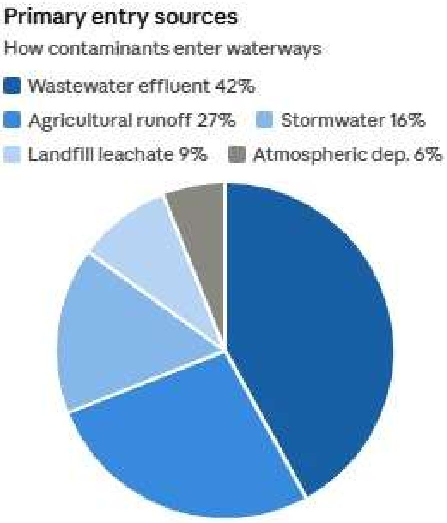

Fig:3 Contaminants leads to Stratification

- **Thermal Absorption Changes (The "Plastic Blanket"):** Microplastics floating on the surface are dark or transparent. They alter the albedo (reflectivity) of the sea surface. Recent models suggest that high concentrations of surface microplastics can slightly increase water temperature by trapping heat, much like a thin blanket.

- **Turbidity Modification:** While natural sediment causes turbidity (cloudiness), microplastics are now so abundant that they physically change how light penetrates the water column. Less light means less heat in surface layers and less vision for predatory fish.

**From Danger to Defense: How to Eradicate or Tolerate Emerging Contaminants in Mangroves**

*Mangroves are the superheroes of the coast—they buffer storms, store carbon, and act as nurseries for fish. Unfortunately, they also act as a "sink" trapping our emerging contaminants. Here is how we can help them fight back.*

**How to Eradicate (The "Clean Up" Strategy)**

- **Biochar Filters:** In tropical nations, researchers are burying "biochar" (charcoal made from mangrove wood waste) in the sediment. This highly porous material acts like a sponge, absorbing pharmaceutical residues and heavy metals before they reach the crabs and roots.
- **Oyster & Mangrove Co-Culture:** Oysters are natural water scrubbers. By farming oysters within mangrove channels, the bivalves filter microplastics and organic contaminants out of the water column, allowing cleaner water to reach the mangrove roots.
- **Constructed Wetlands Upstream:** Before water even reaches the mangroves, local communities can build small "treatment wetlands" using native plants like bullrushes. These plants uptake and break down 80-90% of incoming PPCPs through their root systems.

**How to Tolerate (The "Adaptation" Strategy)**

- **Bio-augmentation with Fungi:** Scientists have isolated fungi species (like *Pleurotus ostreatus*, the oyster mushroom) that grow on mangrove wood and secrete enzymes that literally eat PFAS molecules. Spraying spore solutions on contaminated roots allows the tree to "tolerate" the poison while the fungus removes it.
- **Immuno-Priming Mangroves:** Just like a vaccine for a tree. Nurseries are now pre-treating mangrove seedlings with trace amounts of contaminants. This "priming" turns on the plant's detox genes early, allowing adult trees to survive in moderately polluted waters that would kill un-primed trees.
- **Community "Detox by Dilution" Harvesting:** Local fishermen are being trained to time their opening of water gates. By aligning gate openings with high tides (clean ocean water) rather than low tides (polluted runoff), they naturally dilute the toxin concentration in the mangrove basin, keeping it below the lethal threshold for baby fish.

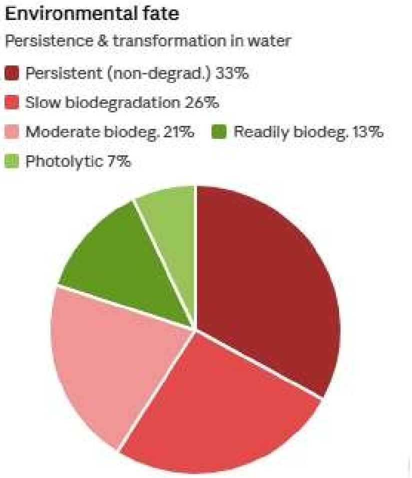

Fig:4 Persistence & transformation in water

## Conclusion: The Price of Convenience

We stand at a strange crossroads in history. We have invented miracle drugs to save our children and non-stick pans to ease our cooking. But those same miracles are turning into nightmares for the fish in the nearest stream. The reality is harsh: we will likely never fully eradicate emerging contaminants from the global ocean. They are a byproduct of 8 billion humans living modern lives. But that does not mean we are powerless. The story of the mangrove teaches us a lesson about resilience. With the right tools—fungal enzymes, biochar sponges, and smart water management—we can help nature "tolerate" the burden we have placed on it. But tolerance is not a free pass. It buys us time. Ultimately, the solution starts not in the ocean, but in the pharmacy cabinet and the laundry room. Switching to natural fiber clothing, disposing of unused medicines via take-back programs (not the toilet), and demanding that water treatment plants upgrade to "quaternary" filtration are not eco-nerd hobbies. They are survival strategies. The next time you take a sip of water or walk along a beach, remember: The water is alive, and it remembers everything we pour into it. Let's make sure that memory is a short one.

ISSN : 2583-0910
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Article ID : 06/VI/06/0626

# MODIFYING INSECT RESPONSES THROUGH SPECIALIZED PHEROMONE AND LURE APPLICATION TECHNOLOGY (SPLAT)

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## Introduction

Specialized Pheromone and Lure Application Technology (SPLAT®) is an innovative controlled-release emulsion system developed to manipulate insect behavior for sustainable pest management in agricultural and forest ecosystems. Unlike conventional pheromone dispensers such as hollow fibers, plastic tubes, or aerosol devices, SPLAT® is a flowable, matrix-based formulation capable of delivering a wide range of biologically active compounds, including sex pheromones, aggregation pheromones, kairomones, attractants, repellents, phagostimulants and insecticides.

SPLAT® technology was acquired by ISCA Technologies in 2004 and has since been adapted for numerous pest species worldwide. The formulation consists of biodegradable inert ingredients, offers low manufacturing costs and can be applied manually, mechanically, or aerially. SPLAT® ensures prolonged pest suppression by protecting semiochemicals against degradation and regulating their emission over a timeframe spanning two weeks to six months. Studies demonstrate that SPLAT® is effective against pests belonging to Lepidoptera, Diptera and Coleoptera and supports mating disruption, attract-and-kill and repellency strategies within integrated pest management (IPM) programs.

## Mechanism of SPLAT® technology

### Physical Properties and Application of SPLAT®

SPLAT® formulations have a paste or cream-like consistency and behave as non-Newtonian, shear-thinning, thixotropic fluids. Their viscosity decreases during stirring or pumping but increases after application, allowing easy handling and strong adhesion to the substrate.

SPLAT® can be applied using:

- Manual tools such as sticks, spatulas, or knives
- Advanced applicators like syringes, grease guns and caulking guns
- Mechanical applicators mounted on tractors, all-terrain vehicles and motorcycles
- Motorized backpack sprayers and aerial application
  These flexible application methods allow SPLAT® to be used across diverse agricultural and forest environments

### Controlled-Release mechanism

The aqueous component of the SPLAT® emulsion provides flowability during application, while the non-aqueous component acts as the controlled-release matrix. Within approximately three hours of application, the aqueous phase dries to form a rain-resistant matrix firmly bonded to the surface, which subsequently delivers a controlled release of active compounds for a duration of two weeks to six months. SPLAT® is a matrix-type (monolithic) diffusion-controlled release system. Active ingredients, usually dissolved in the matrix, diffuse outward following Fick's First Law. Under field conditions, SPLAT® formulations typically exhibit first-order release kinetics, with release rates declining gradually over time.

### Mechanisms of Behavioral Manipulation

#### a) Mating Disruption

SPLAT® releases synthetic pheromones or parapheromones that interfere with insect mate finding through:

- Competitive attraction (false trail following)
- Camouflage of natural pheromone plumes
- Sensory adaptation or habituation
- Sensory imbalance

Experimental studies, particularly in coleopteran pests, show that competitive attraction is often the dominant mechanism. Delayed or prevented mating results in reduced fecundity and fertility, suppressing population growth.

#### b) Attract-and-Kill

In attract-and-kill strategies, SPLAT® combines chemical attractants with insecticides. Target insects are lured to SPLAT® point sources and killed upon contact or experience sublethal effects that reduce reproduction. This approach is effective even at high pest densities.

#### c) Repellency

SPLAT® can also deliver volatile repellents that deter insects from host location, feeding, or oviposition. Repellent formulations modify insect behavior without direct lethality and are useful in push–pull strategies and forest pest protection.

### Functions of SPLAT® in Pest management

SPLAT® performs the following key functions:

1. Controlled and prolonged release of semiochemicals and insecticides
2. Protection of active compounds from environmental degradation
3. Behavioral manipulation of insects
4. Reduction in conventional insecticide use
5. Target-specific pest management with minimal non-target effects
6. Compatibility with IPM programs
7. Flexible and mechanized application methods
8. Effectiveness across multiple insect orders

**Table1: Commercial SPLAT® mating disruption products**

| Product | Pest | Availability |
|---|---|---|
| SPLAT® OFM^(a, b) | *Grapholita molesta* | U.S. & international |
| SPLAT® Cydia^(a) | *Cydia pomonella* | U.S. & international |
| SPLAT® LBAM^(a) | *Epiphyas postvittana* | U.S. & international |
| SPLAT® GM^(a) | *Lymantria dispar* | U.S. & international |
| SPLAT® Tuta^(a) | *Tuta absoluta* | U.S. & international |
| SPLAT® CLM^(a) | *Phyllocnistis citrella* | U.S. & international |

| Product | Pest | Availability |
|---|---|---|
| SPLAT® EC^(a) | *Ectomyelois ceratoniae* | U.S.^(c) & international |
| SPLAT® OFM/PFM^(a) | *G. molesta / Carposina sasakii* | International |
| SPLAT® PBW^(a) | *Pectinophora gossypiella* | International |
| SPLAT® GRAFO/ BONA^(b) | *G. molesta / Bonagota salubricola* | Brazil |

(Mafra-Neto *et al.*, 2013)

**Case studies**

**Carob Moth (*Ectomyelois ceratoniae*) – Mating Disruption**

SPLAT® EC, containing the parapheromone *(Z,E)-7,9,11-dodecatrienyl formate*, was evaluated in date palm orchards. A single seasonal application resulted in:

- Near-complete suppression of male moth captures,
- Fruit protection comparable to repeated malathion dust treatments,
- Reduced environmental and health risks.

This study demonstrated that SPLAT®-based mating disruption can replace conventional insecticide programs without loss of efficacy.

**Fall Armyworm (*Spodoptera frugiperda*) – Attract-and-Kill**

Hook™ FAW, a SPLAT®-based attract-and-kill formulation, was tested in maize fields. Treated plots showed:

- Reduced adult moth populations,
- Lower plant damage compared to insecticide-only treatments.

The results highlighted the value of integrating behavioral manipulation with insecticidal control.

**Tomato Leafminer (*Tuta absoluta*) – Attract-and-Kill**

Field trials using Hook™ Tuta in tomato crops resulted in:

- 78–85% reduction in male moth captures,
- Crop protection comparable to conventional insecticide regimes.

This case study emphasized SPLAT®'s role in managing insecticide-resistant pest populations.

**Oriental Beetle (*Anomala orientalis*) – Mating Disruption and Attract-and-Kill**

SPLAT® OrB was evaluated in blueberry systems for control of oriental beetle. Results showed:

- Strong competitive attraction of males to SPLAT® point sources,
- Reduced female mating success and larval root damage,
- Efficacy equal to or greater than conventional plastic dispensers.

An attract-and-kill version containing cypermethrin caused 100% beetle mortality within 48 hours, even after aging in the field, demonstrating the versatility of SPLAT® formulations.

**Red Palm Weevil (*Rhynchophorus ferrugineus*) – Attract-and-Kill**

Hook™ RPW combined the aggregation pheromone ferrugineol with insecticide. Field trials showed:

- Performance comparable to traditional food-baited pheromone traps,
- Elimination of food bait, water replacement and frequent servicing.

This system provided a low-maintenance alternative for red palm weevil management.

**Mountain Pine Beetle (*Dendroctonus ponderosae*) – Repellent Strategy**

SPLAT® Verb Repel, containing verbenone, effectively protected lodgepole pine trees by:

- Preventing beetle attacks on treated trees,

- Providing spillover protection to nearby untreated trees,
- Performing better than conventional verbenone pouch dispensers.

This study demonstrated SPLAT®'s effectiveness in forest pest protection.

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ISSN : 2583-0910
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Peer reviewed
monthly newsletter

Article ID : 06/VI/07/0626

# GEOSPATIAL MODELLING OF CLIMATE CHANGE IMPACTS ON MARINE FISHERIES USING GIS AND REMOTE SENSING

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## Abstract

Marine fisheries face growing threats from climate-driven changes in ocean conditions, disrupting species distribution, productivity, and coastal livelihoods. This study explores the application of GIS and remote sensing in modelling climate change impacts on marine fisheries, integrating satellite data, oceanographic parameters, and climate scenarios to analyze shifting marine environments. Key stressors including sea surface temperature changes, ocean acidification, deoxygenation, and extreme weather events are assessed for their effects on fish stock dynamics. Species Distribution Models (SDMs) such as MaxEnt are utilized to predict habitat suitability shifts under future climate trajectories. Results highlight the effectiveness of geospatial tools in identifying vulnerable regions, advancing ecosystem-based fisheries management (EBFM), and supporting adaptive conservation strategies, ultimately contributing to climate-resilient fisheries governance and global food security.

**Keywords:** GIS, Remote Sensing, Marine Fisheries, Climate Change, Sea Surface Temperature, Ocean Acidification, Species Distribution Models

## Introduction

Marine capture fisheries supply approximately 20% of global animal-derived protein, yet face escalating pressures from climate-driven changes in oceanographic conditions and marine ecosystem dynamics (FAO, 2018). Climate change is significantly altering the distribution, reproduction, migration, and productivity of marine species, disrupting fish stock dynamics and threatening fisheries-dependent economies, particularly in vulnerable coastal communities with limited adaptive capacity (IPCC, 2021). Shifts in ocean temperature, salinity, and nutrient availability are further reshaping marine food webs and ecosystem functioning, undermining the stability of aquatic food systems.Given the dynamic and complex nature of marine environments, continuous large-scale monitoring is essential. GIS and remote sensing have emerged as effective tools for integrating satellite data, field observations, and climate models, enabling improved spatial visualization, trend analysis, and prediction of ocean conditions. Their combined application supports more adaptive and sustainable fisheries management, helping to safeguard both marine biodiversity and the millions of people who depend on these resources (Pinsky *et al.*, 2020).

## Sea Surface Temperature (SST) Rise

Sea surface temperature (SST) is a key factor controlling marine biological processes and fish physiology. Rising SST due to climate change affects metabolism, growth, and reproduction in fish, and since many species have narrow temperature tolerance ranges, even small changes can cause stress, weaken immunity, and increase mortality (Free *et al.*, 2019). Climate warming is also causing marine species to shift toward cooler regions, either poleward or into deeper waters. These distribution changes disrupt traditional fishing grounds, creating mismatches between fish availability and fishing activities, and posing new challenges for fisheries management (Pinsky *et al.*, 2020). Satellite sensors such as MODIS, AVHRR, and Sentinel-3 provide detailed SST data, which GIS tools use to map warming patterns, identify hotspots, and predict shifts in fish distribution. Long-term analysis of this data supports better climate monitoring and improves fisheries forecasting.

### Ocean Productivity and Chlorophyll Variability

Oceanic primary productivity, driven by phytoplankton, forms the base of marine food webs. Climate change is altering ocean stratification, reducing nutrient mixing and affecting phytoplankton growth, distribution, and seasonal cycles. These changes disrupt the food chain, leading to declines in fish abundance, recruitment, and overall stock availability, ultimately impacting fisheries productivity and long-term yields (Kwiatkowski *et al*., 2020). Recent studies show that phytoplankton productivity is decreasing in some regions due to warming, while increasing in others with better nutrient availability, creating uneven patterns that complicate fisheries management. Satellite sensors such as SeaWiFS, MODIS, and Sentinel-3 OLCI monitor chlorophyll-a levels as an indicator of ocean productivity. GIS integrates this data with fisheries information to map productive zones, track changes over time, and predict fish aggregation areas, helping improve fisheries planning and catch efficiency.

### Ocean Acidification and Deoxygenation

Ocean acidification, resulting from excess $CO_2$ absorption, reduces pH levels and harms calcifying organisms such as corals and shellfish, undermining their structural integrity and broader ecosystem roles (Bindoff *et al*., 2019). Simultaneously, ocean warming and reduced water mixing are expanding oxygen minimum zones (OMZs), forcing oxygen-sensitive fish species to relocate and disrupting marine ecosystem balance and fisheries productivity. Research indicates that the combined occurrence of acidification and deoxygenation significantly reduces habitat quality and availability for a wide range of marine species, threatening their survival and distribution (IPCC, 2021). GIS tools integrate data on ocean pH, dissolved oxygen, and habitat distributions to identify the most climate-vulnerable marine regions, generating risk maps that support conservation efforts and inform more effective fisheries management decisions.

### Extreme Weather Events and Marine Heatwaves

Climate change is increasing the frequency and intensity of extreme weather events such as cyclones, storm surges, and marine heatwaves, with significant consequences for fisheries and coastal communities. Marine heatwaves can trigger coral bleaching, seagrass destruction, and mass fish mortality, causing potentially irreversible ecosystem changes (Smale *et al*., 2019). Cyclones and severe storms further damage fishing vessels, ports, and coastal infrastructure, disrupting livelihoods and fishing operations. Satellite platforms such as Sentinel-1 SAR, Landsat, and MODIS enable near real-time monitoring of these events, while GIS-based change detection techniques allow systematic comparison of pre- and post-event conditions, supporting rapid damage assessment and effective ecosystem recovery and disaster response planning.

## Role of GIS and Remote Sensing in Climate Impact Assessment

### Tracking Changes in Fish Locations and Movement Patterns

Climate-driven shifts in marine species distribution represent one of the most significant consequences of anthropogenic climate change on ocean ecosystems. GIS-integrated Species Distribution Models (SDMs), particularly MaxEnt, incorporate environmental parameters and future climate scenarios to predict species range shifts and habitat suitability changes (Robinson *et al*., 2019). These models help identify emerging fishing grounds, delineate resource-use conflicts, and designate priority conservation areas. They also advance ecosystem-based fisheries management (EBFM) by establishing quantitative linkages between environmental variables and biological responses across multiple trophic levels.

### Monitoring Potential Fishing Zones (PFZ)

Potential Fishing Zone (PFZ) advisories are widely used in countries like India to improve fishing efficiency by guiding fishers to areas with high fish availability. They are developed using satellite data on sea surface temperature (SST) and chlorophyll-a, which indicate favorable conditions for fish aggregation.  However, climate variability and ocean–atmosphere interactions cause PFZ locations to change over time (Purwanto *et al*., 2024). GIS helps in real-time mapping and sharing of PFZ information, enabling fishers to adapt to changing conditions while reducing fuel use and operational costs.

### Habitat Suitability and Ecosystem Modelling

Habitat suitability models evaluate how suitable marine environments are for different species using environmental factors such as temperature, salinity, and productivity. By incorporating climate projections, these models can predict future changes in species distribution (Assis *et al*., 2018). They are important for identifying climate refugia areas less affected by climate change that can support species survival and help in conservation planning and sustainable fisheries management.

### Vulnerability and Risk Assessment

GIS supports decision-making by combining environmental, ecological, and socio-economic data into a single analytical framework, allowing scientists and managers to identify fisheries and coastal communities that are most vulnerable to climate change impacts (Stelzenmüller *et al*., 2018). The vulnerability maps produced through this process provide valuable guidance for policymakers in designing and implementing effective adaptation strategies, including diversification of community livelihoods, improvement of fisheries management practices, and establishment of targeted conservation measures.

### Challenges and Limitations

**Table 1. Challenges in GIS-Based Climate Impact Assessment of Marine Fisheries**

| Challenge | Description | Impact Level |
|---|---|---|
| Limited high-resolution & long-term datasets | Low detail in space and time makes it difficult to closely monitor ecosystems and understand changes over time. | High |
| Infrastructure constraints in developing countries | Limited computing power and lack of funding make it difficult to use and maintain GIS systems. | High |
| High cost of technologies & data processing | Advanced satellites and data processing systems are too expensive for many countries to afford. | High |
| Rapid environmental changes outpace systems | Rapid climate changes are happening faster than current GIS systems can monitor and adapt. | High |

| Challenge | Description | Impact Level |
|---|---|---|
| Uncertainty in climate projections & responses | Uncertainty in models reduces the accuracy of ecological forecasts and long-term fisheries predictions. | High |
| Policy & governance challenges | Poor coordination between institutions makes it hard to turn geospatial data into effective management policies. | High |

## Conclusion

Anthropogenic climate change is significantly impacting marine fisheries, threatening ecological sustainability, food security, and the livelihoods of coastal communities. GIS and remote sensing play a vital role in monitoring these changes, enabling spatial analysis, real-time observation, and predictive modeling. These tools support adaptive and ecosystem-based fisheries management. Integrating technology with effective policies and local knowledge is essential to ensure the long-term sustainability and resilience of marine fisheries.

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ISSN : 2583-0910
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Peer reviewed
monthly newsletter

Article ID : 06/VI/08/0626

# SUSTAINABLE FOOD PRODUCTION: LIMITATIONS AND OPPORTUNITIES IN INDIA

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Across the country, we have clear and growing evidence of soil degradation, groundwater decline, imbalanced and inefficient resource use and climate variability, which raises questions about the sustainability of the present food production system. To address these concerns and secure long-term food and livelihood security. There is a growing need to recognise both the limitations and opportunities in the country. Regenerative practices, integrated farming systems, crop diversification and climate-resilient technologies can strengthen sustainability and resilience. Sustainable improvement also depends on how well farmers, researchers and policymakers align their efforts. This article describes how coordinated actions can shape a food system that meets today's needs without harming resources for future generations.

**Keywords:** Crop diversification, groundwater stress, integrated farming, resource efficiency, soil fertility, water management

Conventional agriculture played a major role in the success of green revolution. But over time continuous use of intensive tillage, monocropping and imbalanced fertilisers and pesticides has weakened the soil and water resources, further threatening sustainable food production. This is where the need for sustainable agriculture arises. Sustainable food production means growing food in such a way that maintains soil fertility, conserves water, protects biodiversity, reduces pollution and keeps the land productive for future generations. Key indicators of sustainability in agriculture are soil organic carbon, soil nutrient balance, soil erosion status and overall soil health. Water-related indicators include groundwater level, water-use efficiency, irrigation efficiency and micro-irrigation coverage. Crop and resource-use indicators focus on yield stability, nutrient-use efficiency, cropping intensity and carbon footprint. Ecological indicators include crop diversity, on-farm biodiversity and pesticide load. Economic and social indicators such as cost of cultivation, benefit–cost ratio, farm income stability and household food security complete the picture of sustainable farming. Evidence from across India shows that many of these indicators are under stress. Table 1 shows that India's soils and water resources are under pressure, with low soil organic carbon, nutrient deficiencies, erosion, groundwater depletion and pollution emerging as major concerns. At the same time, the data also highlight growing opportunities: irrigation coverage is improving, micro-irrigation is expanding and more farmers are adopting crop rotation, conservation practices and digital tools. Overall, these indicators show that while India faces serious sustainability challenges, it also has strong potential to shift toward more resource-efficient and climate-resilient food production. With shrinking per-capita land availability and rapidly declining water tables, India now faces the challenge of producing more food without expanding farmland or exhausting natural resources. This needs a transition to sustainable food production.

**Table 1. Status of these indicators in the country**

| Indicator | Status in India |
|---|---|
| Soil organic carbon (SOC) | • National average SOC: 0.3–0.5%.<br>• Very low SOC (<0.3%): Rajasthan, Haryana, Punjab, Gujarat.<br>• High SOC (>0.75%): NE States, Kerala, Assam. |

| Indicator | Status in India |
|---|---|
| Soil erosion | • India loses 4.9 billion tonnes/year of soil. Worst-affected areas are Shivalik hills (H.P.), Western Ghats, NE States and Chambal ravines. |
| Micronutrient deficiencies | • Zinc, Boron and Sulphur deficient in 36%, 23% and 41% soils of India respectively. |
| Groundwater depletion | • Annual water table fall 0.5–1 m in Punjab, Haryana, Rajasthan, Delhi. Also in Gujarat, Karnataka and Maharashtra. |
| Groundwater pollution | • High nitrate contamination in Punjab, Haryana, UP.<br>• Pesticide contamination in Malwa belt. |
| Stubble burning | • 11–12 million tonnes of paddy straw burned annually in Punjab, Haryana and UP. |
| Adoption of new technologies | • A 2024–2025 survey on farm mechanization estimates that about 47% of agricultural operations in India are mechanized. Crop-specific mechanization- wheat ~69%, rice ~53%, maize ~46% mechanized.<br>• Digital agriculture adoption: Around 30% of farmers use digital tools such as mobile advisories, apps and online weather/market platforms.<br>• Precision agriculture: Still limited only up to 2% of farmers use advanced tools like drones, sensors or IoT-based systems |
| Irrigation coverage | • Irrigated area increased from 49.3% to 55% between 2016–2021. |
| Micro-irrigation coverage | • Around 9 million ha area covered under drip and sprinkler irrigation. |
| Crop rotation | • About under 30 million ha area farmers follow crop rotation. |
| Conservation agriculture | • 2 million ha under zero-tillage, residue retention in Indo-Gangetic Plains. |
| Organic farming | • India has 30% of world’s organic producers while area only 2.7 million ha. |

Looking ahead, three interconnected areas stand out as the foundation of India’s sustainability journey: rebuilding soil health, using water wisely and regeneratively and adopting smarter, climate-resilient crop management systems. When these practices work together, they can help to meet rising food demand, safeguard natural resources, strengthen farm livelihoods and secure long-term environmental stability. Balancing these limitations and opportunities forms the core of India’s pathway towards truly sustainable food production.

## Limitations in India

### Soil and water limitations

Soil erosion (in hilly areas and central India e.g. Madhya Pradesh), soil salinity and sodicity, acidic soils, poor drainage, mining (Jharkhand and Chhattisgarh) are the major soil related limiting factors. Declining groundwater tables (severe in Punjab, Haryana, Rajasthan and Delhi). Contamination of groundwater and surface water from fertilizers and pesticides affecting aquatic life and drinking-water quality. Seawater intrusion has raised salt levels in wells and irrigation sources. Together, these water-related challenges pose serious threats to sustainable food production across the country.

Fig. 1. Composite illustration showing rehabilitation of degraded lands, application of drip irrigation in salt-affected soils, impact of seawater intrusion on soil degradation, and crop losses caused by unpredictable rainfall

**Climate and Weather Risks in India:**

Climate and weather patterns in India are becoming increasingly unpredictable. Frequent droughts, Sudden heat, unexpected rains and cyclones affect crops at critical stages, reducing yields and increasing risk. Most of India's agriculture is rainfed. Frequent droughts, short dry spells, late onset and early withdrawal of monsoon reduce yields and limit fodder availability. These droughts push farmers into financial stress. Heatwaves Reducing Wheat Yield in North India, when temperatures rise above 35–37°C, unpredictable rains and hailstorms damages especially *Rabi* crops, cyclones impacting coastal farming such as Odisha and West Bengal causes loss in rice and coconut farming and bring salty water that contaminates fields and ponds. Soil recovery often takes years after severe cyclone. Climate shifts have increased pest outbreaks for example fall armyworm being a major threat. Sudden change in temperatures and irregular rains favours insect and pest attack in crops causing heavy loss to overall production.

**Socio-economic limitations in Indian agriculture**

Most farmers are smallholder and fragmented holdings (<1.1 ha) with low profitability, making it difficult to adopt modern machinery invest in better seeds, irrigation and improving practices like soil analysis. Labour shortages leaving many farms without timely help. Low literacy levels restrict them to use of improved practices, their awareness about weather forecasts, market prices and advisory services. Additionally, since women rarely own land, they are often excluded from key decisions, making it difficult to shift toward sustainable farming.

Access to affordable credit is limited for small and tenant farmers, forcing many to depend on informal lenders. Frequent market price crashes, such as the recurring tomato and onion crises, expose farmers to heavy losses even in good production years reduce income. These economic barriers directly affect farmers' ability to adopt sustainable and long-term resource-saving practices. Added to this, direct food loss also occurs as post-harvest losses (5–20% in fruits and vegetables) due to price fluctuation and lack of infrastructure.

**Institutional and policy limitations in Indian Agriculture**

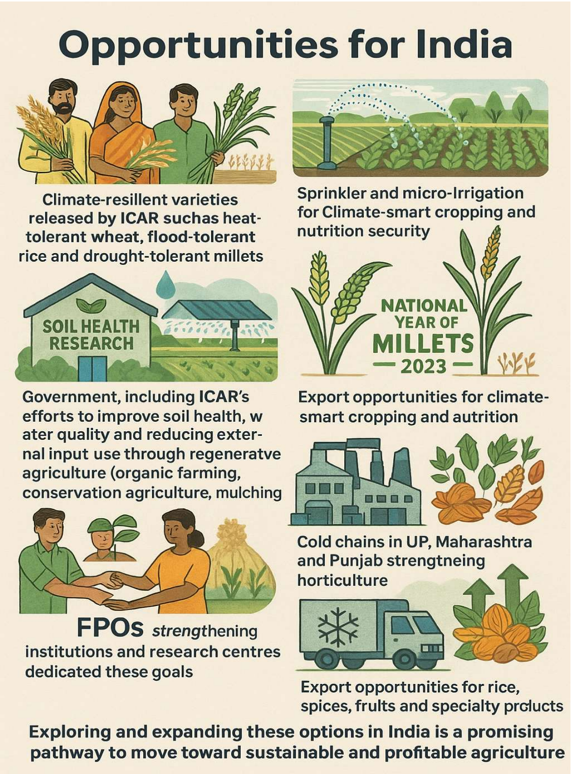
Subsidies on fertilizers and electricity, though helpful, sometimes encourage overuse of urea and excessive groundwater pumping. Lack of extension leaves farmers without timely advice on improved practices and climate-related risks. Due to limited outreach and training, adoption of new technologies and practices is slow.

**Opportunities for India**

**Emerging, Market & Institutional Opportunities**

**Climate-resilient varieties** released by ICAR, such as heat-tolerant wheat, flood-tolerant rice and drought-tolerant millets, help to stabilize yields under extreme weather conditions.

Expanding area under sprinkler and micro-irrigation in Rajasthan, Gujarat, Maharashtra and Tamil Nadu has shown that farmers can save up to 40–50% water while increasing productivity; additionally, crops can be grown in unsuitable areas for traditional irrigation methods.



Government, including ICAR's efforts, focuses on improving soil health, water quality and reducing external input use through regenerative agriculture (organic farming, conservation agriculture, mulching, etc.) by establishing institutions and research centres dedicated to these goals.

India's focus on millets, especially after the national year of millets (2023), presents an opportunity for climate-smart cropping and nutrition security.

On the market side, India is expanding its network of farmer-producer organizations (FPOs) - collective groups of small farmers who pool their produce and resources to gain stronger bargaining power and better access to markets. Also, establishing mega food parks and agro-processing clusters are creating opportunities for value addition, reducing losses and generating rural jobs. The development of cold chains in UP, Maharashtra and Punjab is strengthening the horticulture sector by preventing spoilage. Export opportunities for rice, spices, fruits and specialty products continue to grow, helping farmers tap into global markets. Exploring and expanding these options in India is a promising pathway to move toward sustainable and profitable agriculture.

**Possible solutions for sustainable food production in India**

**Improving resource use efficiencies:** soil is the foundation for all agricultural activities and a medium of supplying all the inputs to the plant. Therefore, improving soil physical, chemical and biological health will improve its nutrient retention, water holding and supplying capacity to plant. Further increasing nutrient and water use efficiencies. Practices such as adding compost, retaining crop residues and using biofertilizers help rebuild organic carbon and restore soil health. Expanding drip, sprinkler and furrow irrigation can save large amount of water. In dryland regions, watershed projects and farm ponds improve groundwater recharge and make agriculture more resilient to drought. Regular soil testing and balanced fertilization prevent nutrient mining and ensure long-term soil health.

**Farm and Crop Management:** Sustainable food production requires diverse and climate-resilient cropping systems. Diversification to millets, pulses and oilseeds reduces water use, improves soil fertility and increases income stability. Farmers can reduce dependency on chemicals by adopting integrated pest management (IPM) such as pheromone traps, bio-pesticides and natural predators. Integrated nutrient management (INM) by combining organic manures, compost, crop residues, green manures, biofertilizers and soil-test–based chemical fertilizers helps in maintaining soil fertility, improving soil structure and reducing long-term nutrient imbalance. Weeds cause significant losses in Indian agriculture, with 15-55% yield loss reported by ICAR-DWR, making Integrated Weed Management (IWM) essential. IWM uses a combination of practices such as crop rotation to break weed life cycles, mulching, timely mechanical weeding, competitive crop varieties and need-based herbicides to minimize yield loss and conserve soil moisture. Stubble mulching and cover cropping further protect the soil surface, reduce erosion and improve soil organic matter.

All the practices together with different farm enterprises (crops with livestock, fishery, horticulture, etc. interacting and recycling each other's byproducts as input) are called Integrated Farming Systems (IFS). It helps recycle nutrients and diversify farm income. Stress-tolerant varieties and agroforestry enhance resilience to climate shocks, strengthening long-term sustainability.

**Economic and policy support:** Economic and policy support play a major role in enabling sustainable practices. Expanding MSP coverage beyond rice and wheat to include millets, pulses and oilseeds to encourage crop diversification. Strengthening PMFBY for timely insurance payouts helps reduce financial risk from climatic variabilities. Improving credit access, especially for small and marginal farmers. Promote adoption of micro-irrigation, machinery and soil health measures by on-farm demonstration. Promote use of renewable energy in agriculture and community-based resource management.

**Success stories**

- Micro-Irrigation Success: In Banaskantha, Kutch and Saurashtra (GJ) micro-irrigation has enabled farmers to diversify and expand area under cotton, cumin, castor, and horticulture crops, often with 20–30% higher yields and significantly reduced water use. Similarly, restoration of traditional water structure such as khadins, tankas, and contour bunds in western Rajasthan has improved moisture storage and enabled successful pearl millet, moong and cluster bean cultivation.

- In cyclone prone areas of West Bengal, farmers adopted salt-tolerant rice varieties such as CSR-36 and Lunishree have reported higher, and more stable yields, even under saline soil conditions.
- Punjab DSR was adopted on over 5 lakh hectares during 2020 monsoon. Benefits such as 15 to 20% Water savings over puddled transplanting, labour cost reduced by ₹4,000 to ₹5,000/ha. Due to early sowing and early harvesting of DSR, provide enough window for timely sowing of wheat and to effectively manage rice crop residues to prevent stubble burning.
- Telangana: Mission Kakatiya (Tank Restoration): Desilted >46,000 village tanks, rising groundwater levels by 0.5–1.2 metres in many mandals (blocks) resultant cropped area increased by 15-20% in tank command villages, and fishery income also increased.

## Summary

Sustainable food production in India is both a challenge and an opportunity. On one hand, declining soil fertility, shrinking water resources, rising input costs and unpredictable weather place real limitations on how long our current farming practices can continue. Farmers feel this pressure every season, as the land demands more care and resources to produce the same harvest. Yet within these challenges lie important opportunities. India knows, the scientific capacity and the farming wisdom needed to rebuild soils, use water more responsibly, diversify crops and adopt climate-smart practices that protect both productivity and the environment. What is needed now is integrated approach of farmers, researchers, policymakers and markets to support this transition with practical technologies, fair prices, reliable extension services and policies that reward sustainable choices. If India can align these strengths, sustainable food production will not be a distant goal but a natural way forward, ensuring that our fields continue to nourish both present and future generations.

ISSN : 2583-0910
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Peer reviewed
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Article ID : 06/VI/09/0626

# GREEN SOLUTIONS FOR A GROWING THREAT: BIOLOGICAL CONTROL OF THE FALL ARMYWORM

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## Abstract

The fall armyworm (FAW) has become a major pest threatening the maize producing regions of India. First reported in 2018 in India, it has spread across the country creating havoc in maize growing regions, causing huge yield loss. Reliance on chemical pesticides may lead to environmental concerns like pollution of air, water and soil and problems like development of insecticide resistance. Biological control methods provide an ecologically safe option for managing fall armyworm. Conservation and augmentation of predators and parasitoids, application of entomopathogens and botanicals offer sustainable and long-term control of fall armyworm.

**Keywords:** Fall armyworm, Biological control, Predator, Parasitoid

## Introduction

Fall armyworm (*Spodoptera frugiperda*) is one of the major insect pests worldwide infesting a wide range of crops and belongs to the family Noctuidae of the order Lepidoptera. Originally native to America, the pest has spread to Africa and Asia. In India, it was initially reported in Shivamogga district of Karnataka on maize crop in May 2018. Due to its polyphagous nature, it is one of the most destructive pests affecting agricultural crops and is known to feed on about 350 plant species. Two strains are reported in FAW, the "maize" strain that primarily feeds on maize and the "rice" strain that primarily feeds on rice crop. In India, FAW is a major pest of maize crop and causes devastating yield losses, especially in the Southern states of India. FAW takes about 30 to 40 days to complete its lifecycle. The female adult moths after mating, lay an average of about 1500 eggs in masses covered by anal tuft hair on the underside of maize leaves. The larvae hatch in about 2 to 3 days and initially feed by scraping the epidermis. The later instars start feeding on the foliage and bore into the stem as well as the cob causing significant yield loss. Hence, it is very important to manage this pest as early as possible. Generally chemical insecticides like emamectin benzoate, spinosad etc., are used for control of this pest. But continuous use of chemicals may lead to environmental pollution, insect resurgence, secondary outbreaks and insecticide resistance. Hence, a green alternative is required. This article discusses various biological control methods for effectively managing FAW like the use of predators, parasitoids, entomopathogens and other biopesticides.

**Fig 1: Fall armyworm (FAW) under a stereo microscope.**

## Predators of FAW

Predators like earwigs, *Orius* spp., ground beetles, spined soldier bug and assassin bug are known to attack and actively feed on eggs and larvae of FAW. Both nymphs and adults of earwigs naturally occur in maize fields and feed on multiple FAW larvae. Predators like *Orius* spp., spined soldier bugs and assassin bugs hunt and pierce their stylets into the larval body and feed on the haemolymph. Ground beetles attack the pupae of FAW in soil. Lady bird beetles and flower bugs are known to feed on eggs of FAW. These predators can be mass multiplied under laboratory conditions and released in the field to control the larval population.

## Parasitoids of FAW

Unlike predators, parasitoids have a highly specialized relationship with their hosts. Egg parasitoids like *Trichogramma* spp. and *Telenomus remus* parasitize the eggs of FAW and their larvae feed on the internal contents of the eggs. Egg-larval parasitoids *Chelonus insularis* and *Chelonus bifoveolatus* parasitize the egg stage of FAW and eventually kill them in the larval stage. Braconids like *Coccygidium luteum*, *Cotesia icipe, Diolcogaster* sp., *Cotesia flavipes* and Tachinids like *Winthemia trinitatis* and *Drino quadrizonula* are larval parasitoids that attack FAW. Larval-pupal parasitoids reported to attack on FAW include *Archytas marmoratus, Sturmiopsis parasitica, Drino quadrizonula* and *Lespesia archippivora*. Conservation and augmentation of these parasitoids will lead to their multiplication and establishment in the field, providing long term and self-sustaining pest control.

## Entomopathogens of FAW

Entomopathogens cause fatal diseases in FAW and play an important role in the biological control of this pest. They include fungi, nematodes, bacteria and viruses. The entomopathogenic bacteria *Bacillus thuringiensis* (Bt) is widely used in agriculture, which produces cry toxins that on ingestion by the larvae disrupt the digestive system of the insect. Various formulations of Bt like thuricide and dipel are available in the market and can be used for sustainable management of FAW. Entomopathogenic fungi like *Beauveria bassiana*, *Metarhizium rileyi* and *Metarhizium anisopliae* infect all stages of FAW and secret toxins into its haemolymph causing death of the insect. Both liquid and solid formulations of these fungi are available in the market and the larva on infection stops feeding, becomes discoloured and eventually dies. Mycelial growth can be observed on the cadavers. Among viruses, baculoviruses are highly effective against FAW. *Spodoptera frugiperda* multiple nucleopolyhedrovirus (SfMNPV) is reported to have highly specific action against FAW. The virus enters the larval body via ingestion and rapidly multiplies in the host causing death within 6 to 8 days. *Heterorhabditis* spp. and *Steinernema* spp. are nematodes that attack the insects especially its soil dwelling stage (pupa). These nematodes penetrate the host tissue and release symbiotic bacteria to kill the pest. All these entomopathogens can be mass produced in the laboratory, have high specificity to target pests, have less impact on the environmental, have self-replication potential and are compatible with most of the components of Integrated Pest Management (IPM).

## Other Biopesticides (Botanicals)

Botanicals are derived from various plant parts like roots, leaves, flowers etc. They possess insecticidal, repellent and antifeedant properties which make them an eco-friendly alternative for managing FAW. Neem oil, Neem Seed Kernel Extract (NSKE) and azadirachtin derived from Neem (*Azadirachta indica*) have repellent, antifeedant and growth deterring ability on FAW. Extracts from plants like tobacco (*Nicotiana tabacum*), jatropha (*Jatropha curcas*) and chrysanthemum (*Chrysanthemum cinerariifolium*) also have insecticidal properties and can be used to manage FAW populations. Leaf extracts of plants like *Vernonia holosenicea* and *Lychnophora ramosissima* have ovicidal action whereas *Melia azedarach* leaf extracts have larvicidal properties. Botanicals hinder the growth of the pest and make them unable to complete their life cycles properly. They are less harmful to beneficial organisms like parasitoids and predators, unlike chemical pesticides and sometimes enhance parasitism by other insects. Contrary to chemical pesticides, frequent application might be required for successfully controlling the pest using botanicals.

## Conclusion

FAW has become a global threat, especially in regions of the world where maize crops are largely cultivated. Due to its rapid spread, large host range and high destructive potential, it is very necessary to control it at the earliest. Heavy reliance on chemical pesticides may lead to development of resistance to insecticide, pollution of the environment and increased cost of farming. Biological control offers a green solution by using predators, parasitoids, entomopathogens and botanicals for the control of this pest. These methods are environmentally friendly and can be easily integrated with other tools of pest management. Incorporation of biological control methods offers a reliable pathway towards sustainable management of fall armyworm.

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ISSN : 2583-0910
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Article ID : 06/VI/10/0626

# BIOREACTORS IN SINGLE-CELL PROTEIN PRODUCTION: DESIGN, APPLICATIONS, AND FUTURE PROSPECTS

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## Abstract

A bioreactor is a controlled system designed to cultivate microorganisms or cells under optimized environmental conditions for the production of valuable biological products. Single-cell proteins (SCPs) represent a promising sustainable protein source amid rising global food demands. This article examines bioreactors as the cornerstone of SCP production, detailing types such as stirred-tank, air-lift, and bubble-column designs optimized for microbial growth. Bioreactors, controlled systems for cultivating microorganisms and cells, are essential tools in various fields, from scientific research to industrial production. The use of a variety of sensors is critical for accurate, real-time monitoring, early problem detection, reproducibility, cost reduction, and increased efficiency. Among its many applications, the production of Single Cell Protein (SCP) has gained considerable importance as a sustainable alternative to conventional protein sources. SCP is derived from microbial biomass such as algae, bacteria, fungi, and yeast, which are capable of rapid growth and high protein accumulation. Bioreactors enable large-scale SCP production by maintaining critical parameters like temperature, pH, aeration, and nutrient supply, thereby enhancing microbial efficiency and yield. This article discusses the concept of bioreactors, their types, and their specific role in SCP production, along with the process, advantages, limitations, and applications. The integration of bioreactor technology in SCP production presents a promising solution to global protein demand, especially in sectors like aquaculture and animal nutrition. Bioreactors enable high yields from waste substrates, positioning SCPs as a viable alternative to conventional proteins.

**Keywords**: Bioreactor, Single-cell protein, Microbial biomass, Scale up, Sustainable protein.

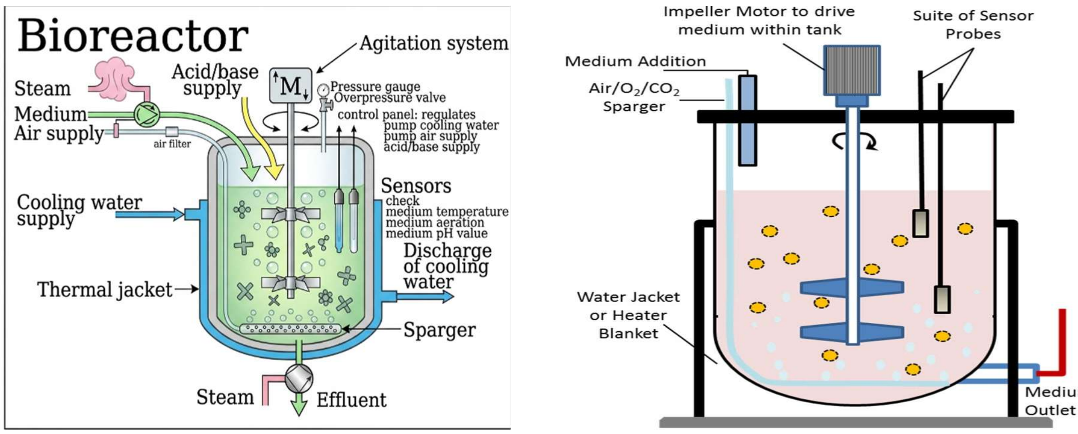
## Introduction

A bioreactor can be described as a specially designed vessel that supports biological processes by providing a controlled environment. It ensures optimal conditions such as proper temperature, pH balance, oxygen supply, and nutrient availability. By maintaining sterility and efficient mixing, bioreactors enhance the growth rate of microorganisms and improve product yield. In 1945, industrial bioreactors could produce 7 trillion units of penicillin. In the second half of the 20th century, bioreactor technology was revolutionized, and improvements and innovations in the process only grew, including sterilization methods, agitation and aeration systems, multivessel systems to produce multiple products in parallel, and the manufacture of equipment with increasingly larger volumetric capacity (Spier *et al.*, 2011). Starting in the 1980s, the world of bioreactors moved beyond microorganisms to cultivating animal and plant cells. In the 21st century, technologies such as automation, artificial intelligence, and 3D printing also became part of new bioreactors, making them automated, versatile, and highly efficient equipment. In addition to these technologies, different bioreactor projects and designs have been developed over the years to ensure the safe and cost-effective manufacturing of biotechnology products Due to this, new types and configurations of bioreactors were built to meet the interests of the industry. Bioreactors are essential in various industries, including biotechnology, pharmaceuticals, agriculture and food production. In the context of SCP, they are used to grow microorganisms in bulk and convert substrates into protein-rich biomass. With the rapid increase in global population and the growing demand for protein-rich food, conventional sources such as agriculture and livestock are facing limitations in meeting nutritional needs. In this context, microbial biotechnology offers a promising solution through the production of Single Cell Protein (SCP). SCP refers to protein derived from microbial biomass such as algae, bacteria, fungi, and yeast. The large-scale production of SCP is made possible through the use of bioreactors, which provide controlled conditions for optimal microbial growth and productivity (Nasseri *et al*., 2011).

Single-cell proteins (SCPs) are nutrient-rich microbial biomasses, like yeast, bacteria, or algae, produced as sustainable alternatives to traditional protein sources such as meat or soy. With global food demand rising projected to increase 50% by 2050 due to population growth. SCPs offer a scalable solution using waste substrates like agricultural residues or industrial effluents. Bioreactors play a pivotal role here, providing controlled environments for microbial growth. This article explores bioreactor types, designs optimized for SCPs, key applications, and emerging trends. In SCP production, bioreactors play a crucial role in maintaining sterile conditions and ensuring efficient conversion of substrates into microbial biomass.

**Fundamental concepts types of Bioreactors for SCP Production**

In recent years, bioreactors designed for submerged fermentation (SmF) and solid-state fermentation (SSF) have gained prominence, driven by the expansion of industrial bioprocesses. This surge aligns with the rise of biorefineries and bioeconomy principles, fuelled by global demands for sustainable processes and products, alongside increased biopharmaceutical and vaccine manufacturing (Kaur and Sharma, 2020). According to biochemical engineering perspective, these bioprocesses operate in liquid media (SmF) or solid media with minimal water (SSF), and may involve agitation (static vs. agitated) or aeration aerated vs. non-aerated (Palladino *et al*., 2024). The aerated STR bioreactor is the most used in the biotechnology industry due to its advantages, such as simple design, versatility (operational flexibility and adaptability to different types of microorganisms), scalability, greater control of cultivation conditions, and reduced risk of contamination. Generally, this type of bioreactor is used in the cultivation of bacterial or yeast microbial cells, as they are less sensitive to shear stress. It is known that one of the main elements of STR bioreactors is the mechanical agitation system, which uses agitators such as blades, propellers, or turbines, according to the needs and particularities of the bioprocess, to promote efficient mixing of the cultivation medium (Figure1 indicates the components and working mechanism of bioreactor). This agitation is crucial to ensure the homogenization of nutrients, uniform distribution of oxygen, and maintenance of ideal conditions throughout the reactor volume. With the advancement of SmF from animal cells, used in the production of some vaccines, biopharmaceuticals, and even in some cases of tissue engineering, modified STR bioreactors have stood out. According to Karnieli (2016) due to the greater sensitivity of animal cells to shear stress, the main modifications that STR bioreactors present that aim at adapting them to the production of biopharmaceuticals. In addition to STR bioreactors, airlift and bubble column types, also known as pneumatic bioreactors, have also gained prominence in recent years. Despite being less used than STRs in the industrial environment, they are necessary equipment for aerated processes, but intense agitation is a critical parameter, as the cells used as fermenting agents are sensitive to shear stress. Airlift bioreactors are based on the draft tube principle, consisting of a cylindrical vessel connected to an aeration system (Xiao *et al*., 2019). The interior of the cylindrical vessel is divided into two distinct parts, being an ascending tube or riser, in which the gas is injected and released in the upper part, and a descending tube or degassed downcomer. Another recent innovation is disposable or single-use bioreactors, also widely used in the pharmaceutical industry for the growth of animal cells in SmF. They are equipment manufactured with high-quality plastic materials, such as low-density polyethylene, polypropylene, or polycarbonate, which eliminates the need for cleaning and sterilization between cultivation batches (Sharma *et al*., 2022).



**(a)** **(b)**

**Figure.1. (a)** Components of bioreactor **(b)** Working mechanism of bioreactor

In recent years, energy consumption and process productivity have been improved using artificial intelligence (AI) with machine learning algorithms adjusting parameters in real time, improving efficiency and reducing waste (Ladner *et al*., 2017). These algorithms predict energy needs and implement predictive control strategies, which are particularly useful in continuous processes (Bradford *et al*., 2018). Bioreactors vary by scale, aeration, and mixing to suit different microbes. Here's a breakdown of common types used for SCPs:

- **Stirred-Tank Bioreactors (STRs)**: Most versatile for lab-to-industrial scales. Impellers ensure uniform mixing and oxygen transfer. Ideal for bacteria like *Methylophilus methylotrophus*.
- **Air-Lift Bioreactors**: Rely on air bubbles for circulation, reducing shear stress for fragile cells like algae. Energy-efficient for large-scale SCP from *Spirulina*.
- **Bubble-Column Bioreactors**: Simple, column-shaped with gas sparging. Suited for fungal SCPs, offering high mass transfer rates.
- **Packed-Bed and Fluidized-Bed Bioreactors**: Immobilize cells on supports for continuous production, minimizing contamination. Selection depends on substrate (e.g., methane for methanotrophs) and product purity needs.

### Bioreactor for SCP Production

The production of Single Cell Protein (SCP) in a bioreactor is a well-organized and tightly regulated process designed to achieve maximum microbial growth and high-quality protein yield (Ma *et al*., 2024). Once selected, a nutrient rich medium is prepared containing essential components such as carbon sources (e.g., molasses or agricultural wastes), nitrogen sources (e.g., ammonia or nitrates), along with vitamins, minerals, and trace elements to support growth and protein synthesis (Samadi *et al*., 2016). The bioreactor and medium are then sterilized using heat, steam, or chemicals to ensure aseptic conditions and prevent contamination. After sterilization, inoculation is carried out by introducing a pure culture into the bioreactor under sterile conditions, initiating the cultivation process. This is followed by the fermentation stage, where microorganisms grow under carefully monitored conditions such as controlled temperature, pH, dissolved oxygen, agitation, and aeration converting nutrients into protein-rich biomass. Once sufficient growth is achieved, the biomass is harvested using methods like centrifugation, filtration, or flocculation. The collected biomass then undergoes downstream processing, including washing, possible cell disruption, and reduction of nucleic acid content to enhance its nutritional value. Finally, the product is dried using techniques such as spray drying or drum drying to produce a stable, protein-rich powder. Overall, SCP production in bioreactors involves a series of interconnected and optimized steps that ensure efficiency, product quality, and economic feasibility.

## Advantages of Single-Cell Protein (SCP) Production in Bioreactors

Single-cell protein (SCP) production in bioreactors offers several significant advantages that make it a promising alternative to conventional protein sources. One of the primary benefits is the high protein yield, as microbial biomass can contain up to 70–80% protein content on a dry weight basis, depending on the organism used, such as bacteria, yeast, or algae. This makes SCP a highly efficient protein source compared to traditional plant and animal proteins. Additionally, microorganisms used in SCP production exhibit a rapid growth rate, often doubling their biomass within a few hours under optimal bioreactor conditions, which allows for faster production cycles and higher productivity. Another major advantage is the reduced requirement for land and water resources (Palladino *et al*., 2024). Unlike conventional agriculture, which depends heavily on arable land and large quantities of water, SCP production can be carried out in compact bioreactor systems with minimal environmental footprint (Figure 2 represents the production flow of SCP). This contributes significantly to sustainable food production, especially in regions facing resource limitations. Furthermore, SCP production in bioreactors supports year-round production, as the process is independent of seasonal variations and climatic conditions. Controlled environmental parameters such as temperature, pH, and nutrient supply ensure continuous and consistent protein output.

Importantly, SCP production enables the utilization of low-cost and waste substrates, including agricultural residues, industrial effluents, and even gaseous carbon sources such as methane or carbon dioxide. This not only reduces production costs but also contributes to waste management and environmental sustainability by converting waste into valuable protein-rich biomass. Overall, these advantages highlight the potential of SCP production in bioreactors as an efficient, sustainable, and scalable solution to meet the growing global protein demand.

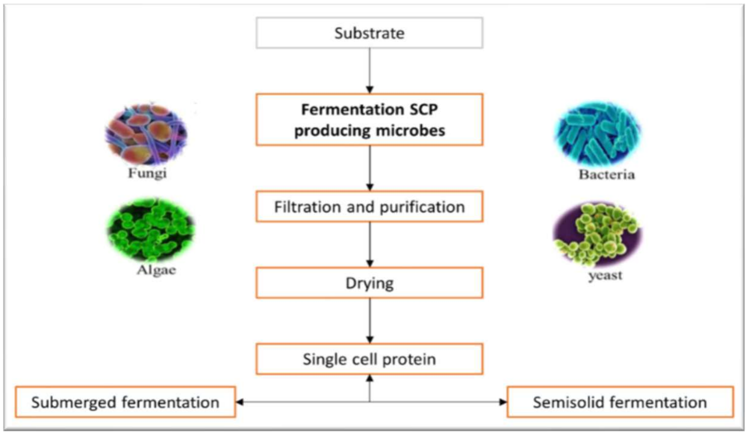


**Figure.2.** Production of Single cell protein

## Challenges in monitoring and Future Prospects

Key challenges in bioreactor-based production include high energy consumption accounting for roughly 20–30% of total costs along with risks of contamination and strict regulatory barriers, particularly for products intended for human consumption. Emerging solutions such as genetically engineered high-yield strains and advanced systems like membrane-aerated hybrid bioreactors offer promising ways to address these issues.

Sensors and control systems are fundamental to bioreactor operation, enabling real-time tracking and adjustment of conditions to enhance the efficiency of chemical, biochemical, and biological processes. Nevertheless, effective process monitoring remains complex due to the wide diversity of bioreactor designs and the biological systems they support. Bioreactors come in many forms, including batch, fed-batch, continuous, magnetic, perfusion, wave, pneumatic, rotating wall, stirred, and newer microfluidic models.

Differences in structural design and modes of operation lead to varying sensor needs and applications across these systems. Despite this diversity, all bioreactors require consistent monitoring of key parameters such as pH, temperature, pressure, flow rates of inputs and outputs, agitation speed, and the concentrations of gases like oxygen, carbon dioxide, and nitrogen (Lim *et al*., 2022). Bioprocess-specific metrics, such as cell growth, enzyme release, nutrient metabolites, and secondary metabolite concentrations, also require tracking. These can differ depending on the cell or microorganism type, metabolic pathway (aerobic or anaerobic), target product (the cell itself or an extra/intracellular one), and cell viability (Mitra and Murthy, 2022). Artificial intelligence (AI) has become a pivotal tool for controlling and monitoring bioreactor processes.

With advancements in computing and programming, it is now possible to create sophisticated analysis algorithms that leverage extensive databases of pre-existing information or real-time data gathered during process monitoring. New sensor technologies aim to develop monitoring methods that supplant spectroscopic approaches, supporting continuous, remote, and integrated oversight. This automation minimizes human errors and contamination risks, which could otherwise derail a bioprocess (Soares *et al*., 2020). A key benefit of online monitoring is the steady data stream for mathematical models, enabling tighter, more precise control and automated optimization of bioreactor conditions (Wang *et al*., 2020). The future of bioreactor systems is set to make a profound impact on both industry and society. New developments emphasize the integration of advanced sensors and automation, allowing real-time monitoring and precise control, which improves overall efficiency and accuracy. These advancements will support the enhanced production of biopharmaceuticals, vaccines thereby strengthening global health as well as biofuels and food products. Beyond industrial benefits, the increasing accessibility of biotechnology is expected to lower barriers to entry, enabling startups and smaller enterprises to participate. This democratization is likely to drive a wider range of innovations aimed at solving diverse societal challenges. Sustainability will play a key role in shaping next-generation bioreactors, with a focus on environmentally friendly materials, energy-efficient processes, and disposable designs that reduce waste and improve recyclability. This aligns with the growing demand for greener industrial practices.

## Conclusion

Bioreactors are essential for the efficient, large-scale production of Single Cell Protein (SCP), as they create controlled environments that optimize microbial growth, boost productivity, and maintain product quality. SCP offers a sustainable and forward-thinking approach to addressing global protein shortages, especially in industries such as aquaculture. Despite its promise, further research and technological progress are required to overcome current challenges and improve its economic viability and public acceptance. Overall, bioreactors are transforming SCP production by enabling sustainable solutions to protein demand. Continued advancements in their design and integration will help fully realize their potential. In biotechnology more broadly, bioreactors play a central role in cultivating microorganisms and cells for a wide range of applications. However, scaling up from laboratory systems to industrial production remains a significant challenge. Addressing this requires a holistic approach that combines automation, computational modelling, and advanced materials. Automation allows precise control over multiple bioreactor systems, enabling real-time monitoring and adjustments that improve efficiency. Looking ahead, the future of bioreactors is highly promising, with ongoing innovations driving more efficient, sustainable, and customized biotechnological processes that can enhance human health and support the development of new therapies.

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ISSN : 2583-0910

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Article ID : 06/VI/11/0626

# INTEGRATED PEST MANAGEMENT (IPM) OF MAJOR INSECT PESTS IN CHILLI

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## Abstract

Chilli cultivation is frequently challenged by insect pests that reduce both yield and fruit quality. Among these, *Thrips parvispinus* and *Helicoverpa armigera* are particularly destructive during the flowering and fruiting stages. Thrips damage plant tissues by sucking sap, while fruit borers directly feed on developing fruits, making them unmarketable. An Integrated Pest Management (IPM) approach combines multiple eco-friendly practices to effectively manage these pests while minimizing reliance on chemical pesticides.

**Keywords:** Chilli, IPM, Thrips, Fruit borer, Sustainable agriculture, Pest management

## Introduction

Chilli (*Capsicum annuum*) is wonder spice, one of the most widely cultivated spice and plays a vital role in agricultural economies. Chilli is an important ingredient in cuisines worldwide, adding flavour, aroma, texture, pungency, and colour to dishes. It is rich in vitamins A, C, K, and B6, along with minerals like potassium, copper, and iron, and also contains dietary fibre. Regular consumption may help reduce LDL (low-density cholesterol), support blood sugar regulation by improving insulin function, and limit microbial growth in foods without refrigeration. Capsaicin, the active compound in chilli, also shows anti-ulcer activity against the bacterium *Helicobacter pylori*. Chilli is affected by various insects, diseases, and nematodes, but pest infestation is a major constraint to achieving optimal yield. Flower thrips are an invasive and threatening pest, while fruit borers are among the most serious pests, especially under warm and dry conditions. Their infestation can result in yield losses of up to 50 - 90%. Continuous and indiscriminate use of insecticides by chilli farmers has led to pest resistance and environmental problems. Therefore, a well-planned Integrated Pest Management (IPM) strategy is essential for sustainable chilli production.

## Nature of Damage and Symptoms

### a. Damage Caused by flower thrips, *Thrips parvispinus*

Thrips are tiny, slender insects that colonize young leaves and flowers. They feed by piercing plant tissues and sucking cell contents, leading to: Upward curling and distortion of leaves, Silvery or bronze discoloration on leaf surfaces, Drying and shedding of flowers, Formation of malformed or undersized fruits (Figure 1).

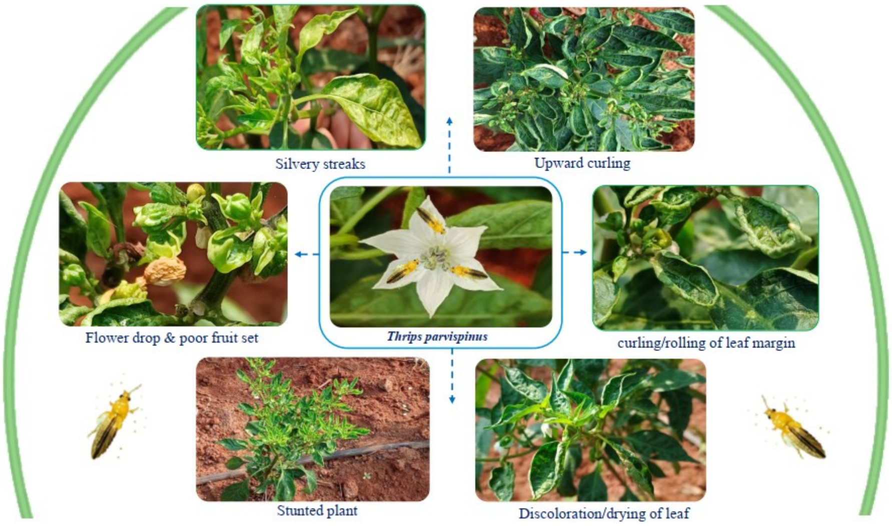


**Figure 1. Symptoms and damage caused by chilli *Thrips parvispinus***

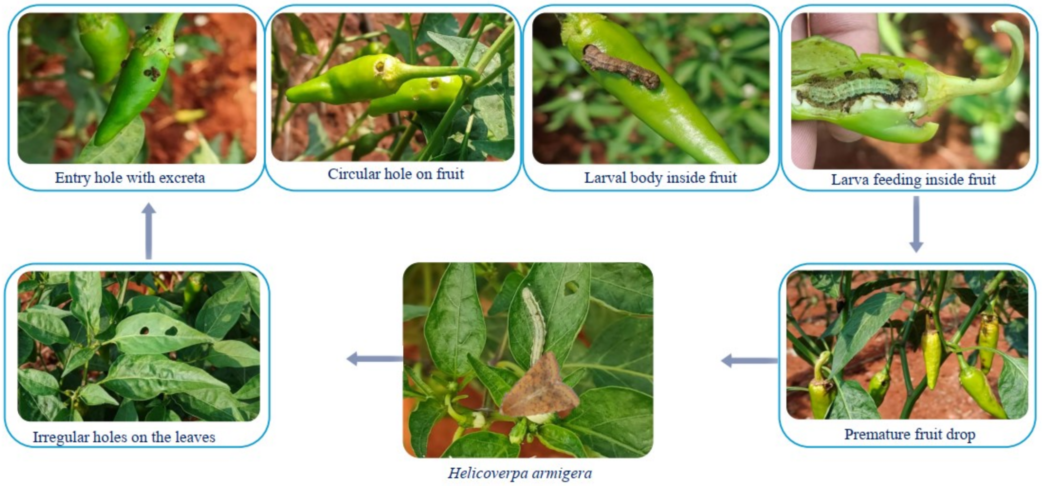


**Figure 2. Symptoms and damage caused by fruit borer, *Helicoverpa armigera***

**b. Damage Caused by Fruit Borer, *Helicoverpa armigera***

Larvae of fruit borer are highly destructive and feed internally on fruits. Their feeding results in: Circular holes on fruits indicating larval entry, Accumulation of excreta near feeding sites, Internal fruit damage making produce unfit for sale, Premature fruit drop under severe infestation (Figure 2).

**Integrated Pest Management Strategies**

A successful IPM program involves the integration of several compatible pest control methods.

**a. Cultural Practices**

Cultural methods form the first line of defense against pest infestation. These include:

- Deep ploughing during summer to expose and destroy soil-borne stages of pests
- To destroy the pupae and residual stages of black thrips, deep summer ploughing should be carried out.
- Apply 250 kg neem cake to the soil to enhance resistance against thrips and fruit borer etc.
- Raising healthy seedlings in pest-free nurseries

- Practice border cropping with 2–3 rows of tall-growing crops such as sorghum, maize, bajra, or fodder grasses, sown densely to act as a barrier against thrips movement.
- Treat seeds with imidacloprid 70 WS (10 g/kg) or dip seedling roots in imidacloprid 17.8% SL (0.5 ml/L) for 30 minutes
- Maintaining recommended plant spacing (Varieties: 60 x 45 cm; hybrids: 75 x 60 cm) to improve air circulation
- Use sprinkler irrigation instead of flood irrigation, as the water spray helps suppress thrips by disturbing their growth and reproduction.
- Avoiding excessive nitrogen fertilizer, which encourages pest build-up
- Practicing crop rotation to break pest life cycles
- Growing marigold as a trap crop to attract fruit borer moths

**b. Mechanical and Physical Methods**

These methods help in reducing pest population at an early stage: Install blue sticky traps (6/acre) for monitoring and 25–30/acre for mass trapping at canopy height; use pheromone traps (6/acre) to catch fruit borer moths. Regularly remove and destroy infested parts and handpick larvae during early infestation.

**c. Biological Control**

Biological agents play a crucial role in maintaining ecological balance:

- Release predators such as *Chrysoperla zastrowi sillemi* @ 50,000 eggs/ ha from 30 DAP (days after planting), feed on thrips and other soft-bodied insects
- Release egg parasitoids like *Trichogramma chilonis* @ 2.5 cc/ha reduce fruit borer population
- Microbial based insecticides like: Application of *Beauveria bassiana* @ 4 g /L (spore load - 1x$10^8$ cfu/g) for thrips and *Bacillus thuringiensis* @ 1kg/ha for fruit borer.
- Spray HaNPV at 1.5 × $10^{12}$ POB/ha mixed with cottonseed oil @ 300 g/ha for effective control of larval stages.
- These agents are safe to beneficial organisms and the environment.

**d. Botanical Control**

Botanical pesticides provide a safer alternative to synthetic chemicals: Apply neem-based insecticide (Azadirachtin 1%) @ 2 ml/L. Application of neem oil 3% @ 2 ml/L, Pongamia oil @ 3 ml/L, reduces feeding and reproduction of pests; Neem Seed Kernel Extract (NSKE 5%) acts as a repellent and growth inhibitor.

**e. Chemical Control (Need-Based Application)**

Chemical pesticides should be applied only when the pest population crosses the economic threshold level (ETL), i.e., 1 larva per plant or 1 damaged fruit per plant for fruit borers, and 2 thrips per leaf or flower for thrips (Table 1), following the crop stage based management schedule (Table 2).

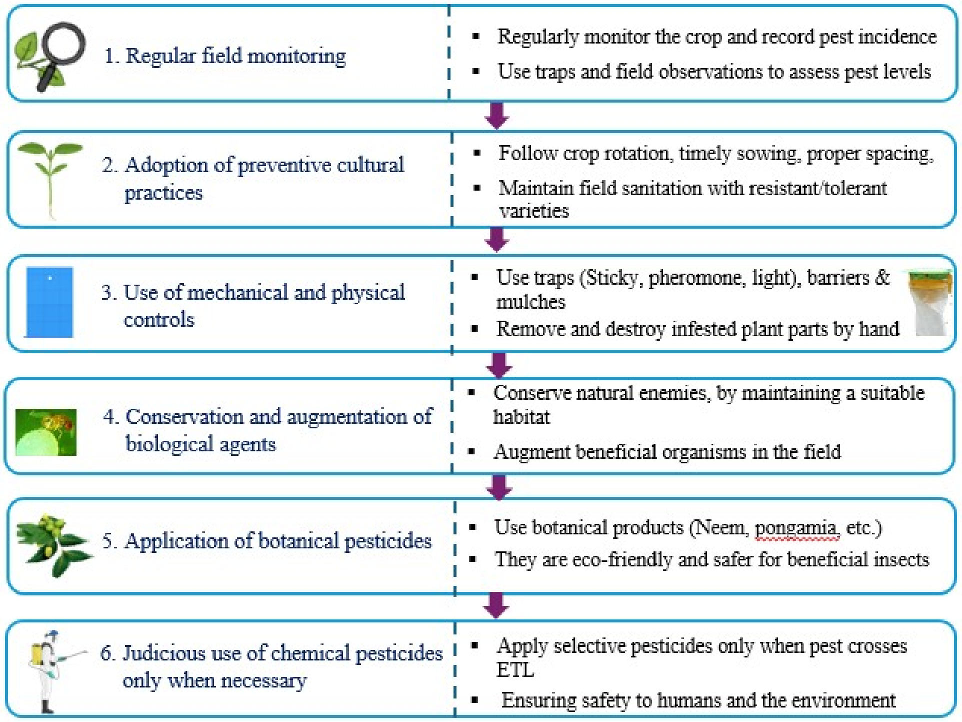
**Table 1. Recommended Insecticides, Dosage and Target Pests for Management of Thrips and Fruit Borer in Chilli**

| S. No | Insecticides | Formulation (g/ml/ha) | Target pests |
|---|---|---|---|
| 1. | Acephate 95 % SG | 790 | Thrips, Fruit borer |
| 2. | Acetamiprid 20 % SP | 250 | Thrips |

| S. No | Insecticides | Formulation (g/ml/ha) | Target pests |
|---|---|---|---|
| 3. | Broflanilide 300 g/l SC | 42-62 | Thrips |
| 4. | Broflanilide 300 g/l SC | 62-84 | Fruit borer |
| 5. | Chlorantraniliprole 18.50 % SC | 150 | Fruit borer |
| 6. | Emamectin benzoate 05 % SG | 200 | Fruit borer & Thrips |
| 7. | Emamectin benzoate 01.90 % EC | 375 | Fruit borer &Thrips |
| 8. | Fipronil 05 % SC | 800 -1000 | Thrips & Fruit borer |
| 9. | Fipronil 18.87 % w/w SC | 250 | Thrips & Fruit borer |
| 10. | Fipronil 80 % WG | 50 - 62.5 | Thrips |
| 11. | Flubendiamide 20 % WG | 250 - 300 | Fruit borer |
| 12. | Imidacloprid 17.80 % SL | 125 - 250 | Thrips |
| 13. | Lambda-cyhalothrin 05 % EC | 300 | Thrips & Fruit borer |
| 14. | Isocycloseram 9.2% W/W DC (10% W/V) DC | 600 | Thrips & Fruit borer |
| 15. | Spinetoram 11.70 % SC | 470 - 500 | Thrips & Fruit borer |
| 16. | Thiacloprid 21.70 % SC | 225 - 300 | Thrips |
| 17. | Tolfenpyrad 15 % EC | 1000 | Thrips |
| 18. | Emamectin Benzoate 01.50 % + Fipronil 03.50 % SC | 500 - 750 | Thrips & Fruit borer |
| 19. | Thiamethoxam 12.60 % + Lambda-cyhalothrin 09.50 % ZC | 150 | Thrips & Fruit borer |

- Proper rotation of insecticides is essential to delay resistance development.

**Integrated IPM Approach:** Effective pest management follows a stepwise approach



1. Regular field monitoring
- Regularly monitor the crop and record pest incidence
- Use traps and field observations to assess pest levels

2. Adoption of preventive cultural practices
- Follow crop rotation, timely sowing, proper spacing,
- Maintain field sanitation with resistant/tolerant varieties

3. Use of mechanical and physical controls
- Use traps (Sticky, pheromone, light), barriers & mulches
- Remove and destroy infested plant parts by hand

4. Conservation and augmentation of biological agents
- Conserve natural enemies, by maintaining a suitable habitat
- Augment beneficial organisms in the field

5. Application of botanical pesticides
- Use botanical products (Neem, pongamia, etc.)
- They are eco-friendly and safer for beneficial insects

6. Judicious use of chemical pesticides only when necessary
- Apply selective pesticides only when pest crosses ETL
- Ensuring safety to humans and the environment

**Table 2. Crop Stage-Based Management Schedule**

| Crop Stage | Target Pest | Recommended Practice |
|---|---|---|
| Nursery | Thrips | Sanitation and neem-based sprays |
| Vegetative | Thrips | Sticky traps and biological agents |
| Flowering | Both pests | Biocontrol + need-based spraying |
| Fruiting | Fruit borer | Pheromone traps + HaNPV |
| Severe infestation | Both | Selective insecticides |

## Advantages of Integrated Approach

- Minimizes dependence on chemical pesticides
- Reduces environmental pollution
- Preserves beneficial insects and biodiversity
- Prevents development of pesticide resistance
- Enhances crop yield and quality

## Conclusion

The combined management of thrips and fruit borer through an Integrated Pest Management approach ensures effective and sustainable pest control in chilli cultivation. By integrating cultural, biological, and chemical methods in a balanced manner, farmers can achieve higher productivity while maintaining environmental safety.

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ISSN : 2583-0910

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Article ID : 06/VI/12/0626

# CLIMATE-SMART FARMING: CAN INDIAN AGRICULTURE SURVIVE EXTREME WEATHER?

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## Abstract

Indian agriculture is increasingly under threat due to climate change, with rising temperatures, erratic rainfall, droughts, and floods becoming more frequent. These changes are reducing crop productivity and putting farmers' livelihoods at risk. Climate-Smart Agriculture (CSA) offers a sustainable solution by improving productivity, strengthening resilience, and reducing environmental impact. This article explores the challenges faced by Indian agriculture and highlights practical climate-smart solutions for a sustainable future.

**Keywords:** Climate change, Climate-smart agriculture, Indian agriculture, Sustainable farming, Resilience, Food security

## Introduction

Agriculture plays a vital role in India's economy, supporting nearly half of the population. Traditionally, farming practices have depended heavily on predictable seasonal cycles, particularly the monsoon. However, climate change has significantly disrupted these patterns, making agricultural activities increasingly uncertain and risky. In recent years, farmers have experienced delayed monsoons, unseasonal rainfall, and prolonged heatwaves. These changes not only affect crop productivity but also heighten the vulnerability of small and marginal farmers. As climate-related risks continue to intensify, adopting sustainable and adaptive farming approaches has become essential.

## Impact of Climate Change on Indian Agriculture

Climate change is already exerting significant and visible impacts on Indian agriculture. Rising temperatures are shortening crop growth cycles and reducing yields, especially for staple crops such as wheat and rice (Figure 1). Erratic rainfall patterns have become a major concern, with some regions facing severe droughts while others experience sudden flooding. Excess rainfall contributes to soil erosion and nutrient depletion, whereas prolonged dry spells reduce soil moisture and agricultural productivity. Furthermore, changing climatic conditions are influencing the spread and intensity of pests and diseases, leading to increased crop damage. These challenges are making traditional farming practices less reliable and increasing economic risks for farmers.

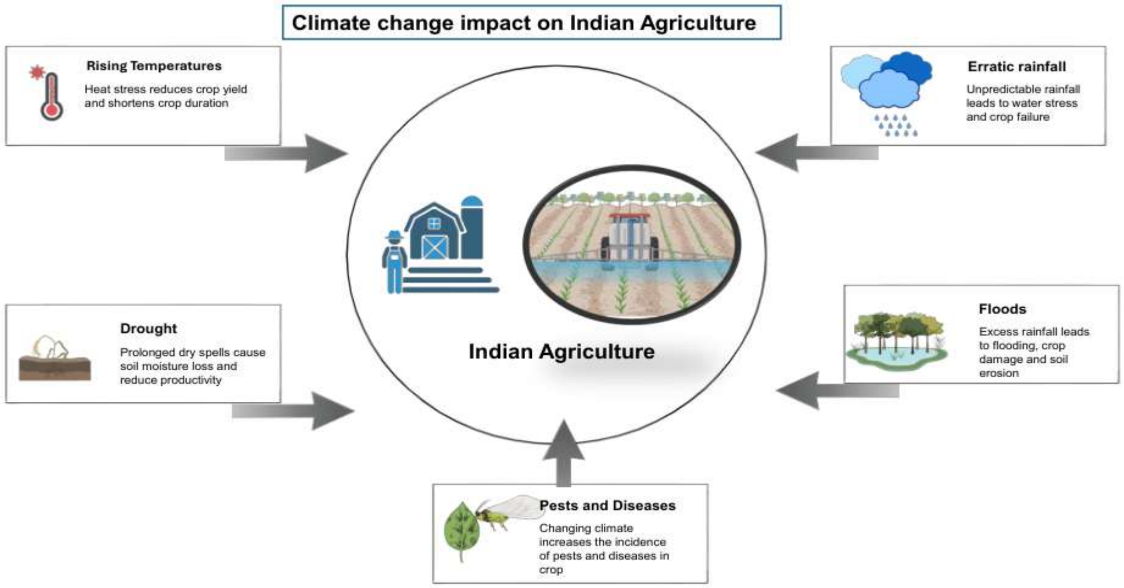

**Figure 1. Climate change impact on Indian Agriculture**

## Climate-Smart Agriculture (CSA)

Climate-Smart Agriculture (CSA) is an integrated approach aimed at addressing the challenges posed by climate change (Figure 2). It focuses on three primary objectives: enhancing agricultural productivity, strengthening resilience to climate variability, and reducing environmental impact. CSA promotes the efficient use of natural resources such as soil, water, and energy. By combining traditional knowledge with modern scientific innovations, it enables farmers to adapt to changing climatic conditions while ensuring sustainable agricultural production.

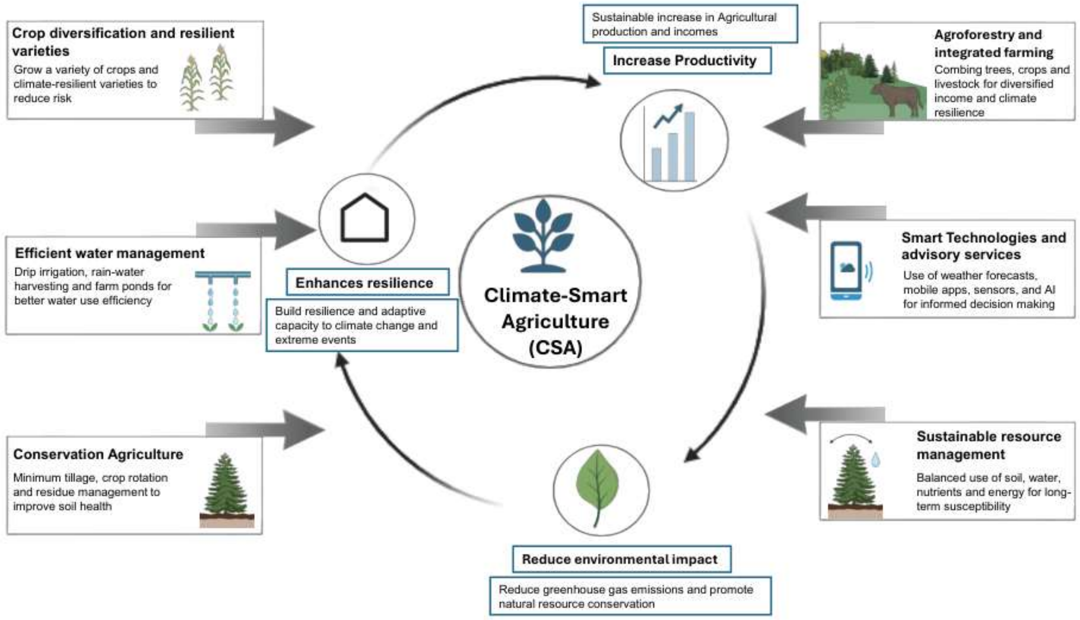

**Figure 2. Climate-Smart Agriculture (CSA)**

### Climate-Smart Practices

Farmers across India are increasingly adopting climate-smart practices to cope with environmental challenges (Table 1). Crop diversification, which involves cultivating multiple crops, helps reduce the risk of total crop failure. The adoption of drought-tolerant and heat-resistant crop varieties enables farmers to maintain productivity under stress conditions. Efficient water management techniques, such as drip irrigation, sprinkler systems, and rainwater harvesting, improve water use efficiency and reduce dependence on erratic rainfall.

Conservation agriculture practices-including minimum tillage, crop rotation, and residue management-enhance soil health and improve moisture retention. Agroforestry and integrated farming systems, which combine crops, livestock, and trees, provide diversified income sources and strengthen resilience. In addition, modern technologies such as mobile-based advisory services, weather forecasting, remote sensing, and precision farming tools support informed decision-making and reduce agricultural risks.

### Role of Government and Policies

Government initiatives play a crucial role in promoting climate-smart agriculture. Programs such as the National Mission for Sustainable Agriculture (NMSA), Pradhan Mantri Krishi Sinchai Yojana (PMKSY), and crop insurance schemes aim to support farmers in adapting to climate change. These initiatives focus on improving water management, encouraging sustainable practices, and providing financial protection against crop losses. However, effective implementation and increased awareness are essential to ensure that these benefits reach all farmers.

**Table 1. Climate-Smart Farming Practices and How They Help Farmers**

| Climate-Smart Practice | What It Means | Benefit to Farmers |
|---|---|---|
| Crop Diversification | Growing different crops instead of relying on a single crop | Reduces risk of total crop failure |
| Climate-Resilient Varieties | Using drought- and heat-tolerant crop varieties | Maintains yield under extreme weather conditions |
| Drip Irrigation | Delivering water directly to plant roots in a controlled manner | Saves water and improves efficiency |
| Rainwater Harvesting | Collecting and storing rainwater for agricultural use | Reduces dependence on irregular rainfall |
| Conservation Agriculture | Practicing minimum tillage and crop rotation | Improves soil fertility and moisture retention |
| Agroforestry | Integrating trees with crops and livestock | Provides additional income and environmental protection |
| Smart Technologies | Using weather forecasts, mobile apps, and sensors | Supports better decision-making and reduces risks |

### Benefits of Climate-Smart Agriculture

The adoption of climate-smart agriculture offers multiple advantages. It helps stabilize crop yields under unpredictable weather conditions, thereby enhancing food security. Farmers can increase their income through diversified farming systems and improved resource management. CSA also strengthens resilience by enabling farmers to withstand climate shocks such as droughts and floods. Additionally, it contributes to environmental sustainability by conserving soil, reducing water wastage, and lowering greenhouse gas emissions.

## Challenges in Adoption

Despite its benefits, the adoption of climate-smart agriculture remains limited in many regions. A major challenge is the lack of awareness and technical knowledge among farmers. Financial constraints often prevent small and marginal farmers from investing in advanced technologies and infrastructure. Limited access to credit, insurance, and extension services further restricts adoption. Moreover, gaps in policy implementation and insufficient technical support hinder the large-scale promotion of these practices.

## The Way Forward

To ensure the future of Indian agriculture, a coordinated effort is required from government, researchers, and farmers. Increasing awareness through training and extension programs is essential to promote climate-smart practices. Financial support in the form of subsidies, credit facilities, and insurance can reduce the burden on farmers. Investment in research and innovation is needed to develop affordable and region-specific technologies. Strengthening digital agriculture and advisory services can further empower farmers to make better decisions.

## Conclusion

Indian agriculture is at a critical juncture due to the growing impacts of climate change. Climate-Smart Agriculture offers a practical and sustainable pathway to address these challenges. By adopting CSA practices, farmers can enhance productivity, improve resilience, and secure their livelihoods. With stronger policy support, increased awareness, and continued innovation, climate-smart farming can ensure a stable and sustainable future for Indian agriculture.

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ISSN : 2583-0910
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Peer reviewed
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Article ID : 06/VI/13/0626

# DATA MINING TECHNIQUES AND THEIR APPLICATIONS IN APPLIED RESEARCH

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In today's digital era, organizations and researchers are confronted with an ever-increasing volume of data generated from diverse sources such as business transactions, healthcare systems, scientific experiments, social media, and sensor technologies. Transforming this vast amount of raw data into meaningful knowledge has become essential for decision-making, innovation, and problem-solving. Data mining is the process of extracting knowledge or insights from large amounts of data using various statistical and computational techniques. Alternative names of Data Mining is Knowledge Discovery (mining) in Databases (KDD), Knowledge Extraction, Data/Pattern analysis and Business Intelligence *etc*., (Patel and Patel, 2016).

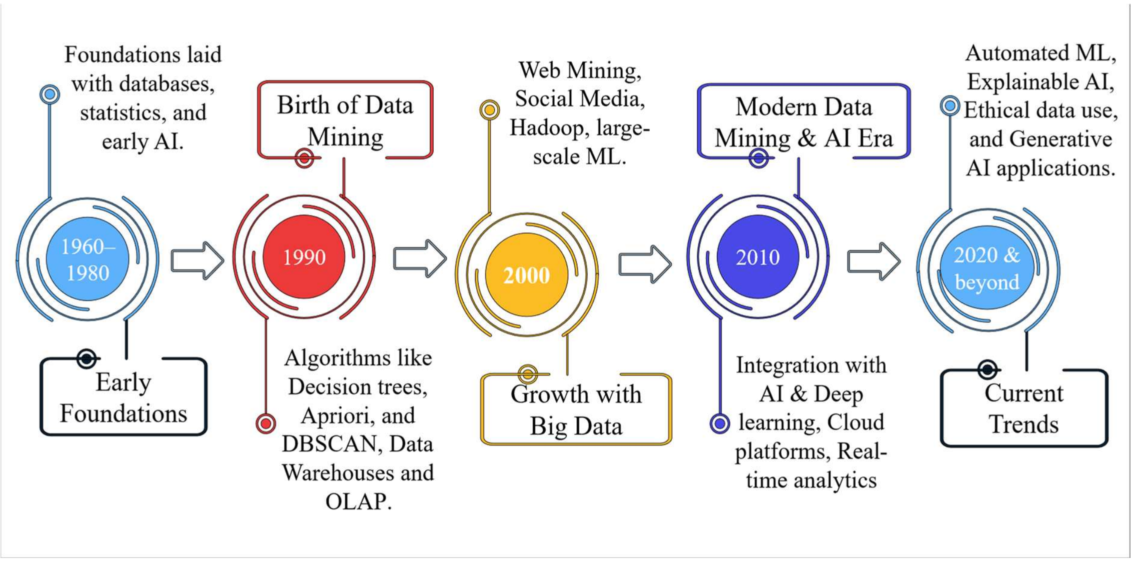
### Why Data for Mining?

- **To Find Patterns and Trends:** Identifies hidden relationships and regularities in large datasets.
- **To Support Better Decisions:** Provides data-driven insights for accurate and informed decision-making.
- **To Predict the Future:** Uses past data to forecast future outcomes and behaviour.
- **To Gain Competitive Advantage:** Helps improve efficiency, strategy, and performance over competitors.
- **To Detect Problems & Risks:** Identifies anomalies, errors, and potential risks at an early stage. Source: https://www.google.com

### Knowledge Discovery in Database (KDD) Process or Data Mining Process

1. **Data cleaning**: In this Phase handle missing value, noise, Inconsistencies & Remove duplications from the data.
2. **Data integration**: In this Phase multiple data sources, often heterogeneous, may be combined in a common source.
3. **Data selection**: In this phase we have to decide the data relevant to the analysis is decided on and retrieved from the data collection.
4. **Data transformation**: In this phase the selected data is transformed into forms that is appropriate for the mining procedure.
5. **Data mining**: It is the crucial step in which Different Algorithms/techniques are applied to extract useful patterns and trends.
6. **Pattern evaluation**: In this step, strictly interesting patterns representing knowledge are identified based on given measures.
7. **Knowledge representation**: It is the final phase in which the discovered knowledge is visually represented to the user. Present the mined knowledge in understable ways like charts, dashboards and reports. Source: https://www.geeksforgeeks.org/

## History of Data Mining



Source: Madhushree and Vidya (2022)

**Tools used in Data Mining**: Python, R-Programming, IBM SPSS, KNime, WEKA tool, RapidMiner, Orange

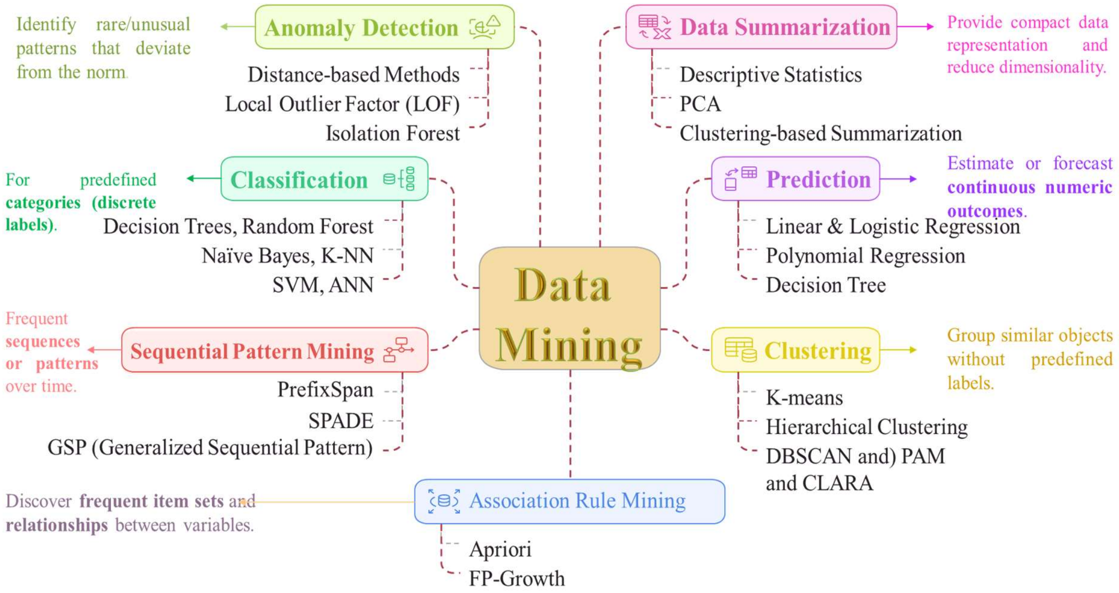
Source: https://www.spiceworks.com/

**Applications of Data Mining in Applied Research:**

1. **Healthcare and Medicine**: Used for disease diagnosis, patient risk prediction, treatment outcome analysis using classification and predictive models.
2. **Business, Economics and Finance:** Applied for customer segmentation, demand forecasting, credit risk assessment using clustering and regression techniques and Supports fraud detection.
3. **Environmental and Agricultural Sciences:** Used for crop yield prediction, weather forecasting, analyse soil health, water use efficiency and climate change impacts.
4. **Social Sciences and Humanities:** Applied to analyse survey data, social behaviour and demographic patterns using clustering and association analysis.
5. **Engineering and Technology:** Used for fault detection, predictive maintenance, and quality control using machine learning models.
6. **Government and Public Policy:** Helps in policy planning, governance through predictive and pattern analysis, welfare targeting, and population studies.
7. **Education and Learning Analytics:** Applied to analyse student performance, dropout prediction, personalized learning pathways and Supports curriculum improvement.

Source: https://www.google.com/

**Data Mining Methods:**



Harnessing Data Mining: Techniques and Algorithms For Applied Research

Source: Kohail and El-Halees (2011), Patel and Patel (2016), https://www.educba.com/

**Current Advancements in Data Mining**

- Integration with Big Data Technologies
- Graph Mining and Network Analysis
- Machine Learning and Deep Learning Integration
- Cloud-Based Data Mining
- Privacy-Preserving and Ethical Data Mining

Source: https://www.geeksforgeeks.org/

**Limitations in Data Mining**

- Data Quality Issues
- Model Bias
- Privacy Concerns
- High Cost & Complexity

Source: https://www.geeksforgeeks.org/

**Conclusion**

The data mining techniques like classification, clustering, regression, association rule mining and prediction are widely used in applied research for tasks such as yield prediction, soil fertility analysis, weather forecasting and prediction student exam performance. WEKA is a user-friendly and effective tool for applying data mining techniques in the applied research domain, especially useful for researchers. Technical skills and domain knowledge are essential for correctly applying and interpreting data mining result. Popular methods like ANN, RF, J48 and DT (for classification), K-means and DBSAN clustering (for grouping data), MLR, Ensemble model (for yield prediction) are frequently used in data analysis.

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ISSN : 2583-0910
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Article ID : 06/VI/14/0626

# DIGITAL TWIN TECHNOLOGY IN PROTECTED CULTIVATION

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## Abstract

Digital Twin Technology is an emerging innovation transforming modern agriculture, especially in protected cultivation systems such as greenhouses. It creates a virtual replica of a real farming environment that continuously receives and analyzes real-time data from sensors, climate systems, and crop conditions. By integrating advanced data analytics and predictive modeling, it enables farmers to monitor, simulate, and optimize agricultural processes—addressing key challenges such as unpredictable yields, inefficient resource use, and climate variability. This article explores the concept, components, and application of Digital Twin Technology in protected cultivation, highlighting its role in yield prediction, input optimization, economic benefits, sustainability, and future potential.

**Keywords:** Digital Twin Technology, smart farming, precision agriculture, greenhouse innovation, yield prediction, real-time monitoring, IoT sensors, AI-driven decisions, resource optimization, sustainable agriculture

## Introduction

Agriculture is undergoing a transformation driven by digital technologies that are making farming more efficient and sustainable (Fuller *et al.*, 2020). Digital Twin Technology is particularly valuable in protected cultivation systems like greenhouses, where year-round crop production requires precise environmental control. However, challenges such as resource wastage and inaccurate yield prediction persist (Howard *et al.*, 2021). Digital Twins address these by creating a virtual copy of the farm environment that can be monitored and controlled in real-time, combining data analysis, automation, and predictive modeling to enable data-driven decision-making and improve both productivity and climate resilience (Nasirahmadi & Hensel, 2022).

## Digital Technologies and Digital Twin Concepts

### Evolution in Agriculture

Agricultural technology has evolved from simple machinery to advanced precision farming using remote sensing, GIS, and IoT—collectively forming the foundation for Digital Twin systems (Escribà-Gelonch *et al.*, 2024). Digital Twins represent the next step, integrating these technologies into a unified platform that provides a holistic view of the farming system, enabling better coordination across soil, water, climate, and crop management (Wang, 2024).

### What is Digital Twin Technology?

A Digital Twin is a dynamic virtual model of a physical system that uses real-time data from sensors, weather stations, and historical records to replicate farm or greenhouse conditions. Through machine learning, it continuously learns and refines its predictions, helping farmers adapt to changing conditions and facilitating collaboration among researchers, agronomists, and policymakers on a shared analytical platform (Singh *et al.*, 2021; Peladarinos *et al.*, 2023).

**Digital Twin in Protected Cultivation**

Protected cultivation systems are ideal for Digital Twin implementation due to their controlled, data-rich environments. Digital Twins leverage data from automated irrigation and climate control systems to model plant growth, nutrient uptake, and environmental interactions (Chaux *et al.*, 2021). They also enhance adaptability—farmers can simulate adjustments to temperature, humidity, and light intensity before implementing them, improving planning and risk management for high-value crops (Howard *et al.*, 2021).

**Types of Digital Twins in Agriculture**

Digital Twins in agriculture are categorized by complexity: (i) Component-level twins focus on individual elements such as soil or a single plant; (ii) System-level twins represent the entire farming system integrating crops, environment, and infrastructure; and (iii) Process-level twins simulate specific agricultural processes such as crop growth cycles or nutrient cycling (Pylianidis *et al.*, 2021). The maturity of these systems is growing, with a significant surge in peer-reviewed publications since 2022 (Tagarakis *et al.*, 2024).

**System Components and IoT Integration**

A Digital Twin system for protected cultivation consists of sensors and IoT devices, a cloud-based data platform, simulation models, AI algorithms, and an intuitive user interface. Sensors capture real-time data on soil moisture, temperature, $CO_2$ concentration, and light intensity, which is transmitted to the cloud for processing (Bakthavatchalam *et al.*, 2022). AI algorithms transform this raw data into actionable insights, predicting future conditions and recommending corrective actions. Advances in sensor technology have made these devices more accurate and affordable, broadening access for smallholder farmers (Subeesh & Chauhan, 2025; Kalyani *et al.*, 2024; Slimani *et al.*, 2024).

**Key Benefits**

**Yield Prediction**

Digital Twins significantly improve yield prediction accuracy by continuously monitoring crop growth and environmental conditions using advanced algorithms. Early and accurate yield forecasts allow better planning of harvesting, storage, and marketing, and help mitigate risks from price fluctuations and market demand shifts (Bhattacharya & Pandey, 2023; Kalyani & Collier, 2021).

**Input Optimization and Economic Benefits**

By analyzing real-time data alongside crop requirements, Digital Twins provide precise recommendations for water, fertilizer, and energy use, reducing production costs and minimizing environmental impact. Precise irrigation reduces water waste, while optimized fertilization prevents soil and water pollution (Abioye *et al.*, 2022; Cesco *et al.*, 2023). Economically, these efficiencies increase income while reducing costs. Although initial investment may be high, the long-term return through resource savings and yield improvements makes Digital Twin Technology a valuable asset (Attaran *et al.*, 2023; Gallego-García *et al.*, 2023).

**Environmental Sustainability**

Digital Twins promote sustainability by optimizing resource use, minimizing chemical runoff, and conserving natural resources. They support climate-smart agriculture by enabling simulation of diverse climate scenarios, helping farmers develop proactive strategies for managing variability and advancing global food security goals (Purcell & Neubauer, 2023; Escribà-Gelonch *et al.*, 2024).

## Challenges and Future Prospects

### Challenges

Digital Twin adoption faces hurdles including high implementation costs, technical complexity, data dependency, and limited digital infrastructure in rural areas (Botín-Sanabria *et al.*, 2022). The need for skilled personnel and ensuring data accuracy are also critical. Key barriers identified in recent literature include technology immaturity, high capital investment, and low digital literacy among smallholder farmers (Gnanamalar & Ayyasamy, 2025).

### Future Prospects

Continued advances in AI, robotics, and data analytics are expected to make Digital Twin solutions more affordable and scalable. Integration with UAVs and satellite imaging will further improve real-time monitoring. As these technologies mature, Digital Twin systems are expected to evolve toward fully autonomous, prescriptive farming—representing a cornerstone of Agriculture 4.0 and beyond (Wang, 2024; Kalyani *et al.*, 2024).

## Conclusion

Digital Twin Technology represents a major advancement in modern agriculture, particularly in protected cultivation. By enabling real-time monitoring, accurate yield prediction, and efficient input optimization, it empowers farmers to improve productivity and sustainability. Despite current challenges related to cost, infrastructure, and technical expertise, continued innovation, supportive policies, and declining technology costs position Digital Twins as an essential tool for the future of smart, data-driven, and environmentally responsible farming.

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ISSN : 2583-0910

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Peer reviewed
monthly newsletter

Article ID : 06/VI/15/0626

# COLLAR ROT AND DEFOLIATORS OF GOLDENROD: A REVIEW

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**Abstract**

Goldenrod (*Solidago spp.*) is an economically important ornamental crop widely used in the floriculture industry due to its attractive inflorescences and extended vase life. However, its production is significantly constrained by biotic stresses, notably collar rot disease and leaf-eating caterpillars. Collar rot, primarily caused by soil borne fungal pathogens, leads to severe plant mortality, while defoliating caterpillars reduce photosynthetic efficiency and aesthetic value. This review presents an in depth analysis of the etiology, epidemiology, symptomatology and identification of these major constraints, along with their biological behavior and field level diagnostic distinctions.

**Keywords:** Goldenrod (*Solidago spp.*), collar rot, *Sclerotium rolfsii*, *Rhizoctonia solani*, defoliators, *Spodoptera litura*, *Helicoverpa armigera*, pest and disease identification

## Introduction

Goldenrod (*Solidago spp.*), belonging to the family Asteraceae, is a popular filler flower in global floriculture. It is cultivated extensively due to its adaptability, high yield, and market demand. However, intensive cultivation practices, monocropping, and favorable environmental conditions often promote the development of diseases and insect pests. Among these, collar rot and leaf-eating caterpillars are particularly destructive, causing both qualitative and quantitative losses. Understanding their identification and biological characteristics is essential for developing effective management strategies.

## Collar rot disease in Goldenrod

### Causal organisms and taxonomy

Collar rot is mainly caused by:

- *Sclerotium rolfsii* (teleomorph: *Athelia rolfsii*)
- *Rhizoctonia solani*

This fungi belong to:

- **Kingdom:** Fungi
- **Phylum:** Basidiomycota (for *Sclerotium rolfsii*)
- **Class:** Agaricomycetes

They are **necrotrophic pathogens**, meaning they kill host tissues and feed on dead matter.

### Disease cycle and epidemiology

- The pathogen survives in soil as sclerotia or mycelium
- Infection occurs under high temperature (25–35°C) and high humidity
- Sclerotia germinate and infect the plant at the collar region
- Spread occurs through irrigation water, soil movement and infected debris
- Dense planting and poor drainage enhance disease incidence

**Symptom development (Progressive stages)**

**Early Stage:**

- Slight yellowing of lower leaves
- Reduced vigor

**Intermediate Stage:**

- Water soaked lesions near soil level
- Browning and softening of stem tissues

**Advanced Stage:**

- Profuse white mycelial growth
- Formation of round brown sclerotia
- Complete wilting and collapse of plant

**Histopathology and infection mechanism**

- Fungal hyphae penetrate plant tissues through natural openings or wounds
- Secretion of cell wall degrading enzymes (cellulases and pectinases)
- Rapid destruction of cortical tissues leading to vascular blockage
- Disruption of water transport causes wilting

**Diagnostic identification**

- Presence of mustard seed-like sclerotia is a key diagnostic feature
- Disease localized at soil plant interface
- Foul smell due to tissue decomposition
- Confirmed through microscopic examination or fungal isolation

**Management of collar rot:**

Collar rot in goldenrod (*Solidago spp.*) is managed by good drainage, proper spacing and removal of infected debris. Application of biocontrol agents like *Trichoderma* spp. helps suppress soil borne pathogens. In severe cases, soil drenching with fungicides such as carbendazim or captan is effective.

**Leaf eating caterpillars in Goldenrod**

**Species and classification**

Major defoliators include:

- *Spodoptera litura* (Family: Noctuidae)

- *Helicoverpa armigera* (Family: Noctuidae)
- *Spilarctia obliqua* (Family: Erebidae)

These are **polyphagous pests** affecting multiple crops

**Life cycle and biology**

**Egg Stage:**

- Eggs laid in clusters on leaf surfaces
- Covered with hair or scales (in *Spodoptera*)

**Larval Stage (Damaging stage):**

- 5–6 instars
- Duration: 2–3 weeks
- Highly voracious feeders

**Pupal Stage:**

- Pupation occurs in soil or plant debris

**Adult Stage:**

- Moths emerge, mate, and lay eggs, completing the cycle

**Feeding behavior and damage mechanism**

- Early instars feed on leaf epidermis
- Later instars cause complete defoliation
- Feeding reduces photosynthetic activity
- Leads to stunted growth and poor flowering
- Secondary infections may occur through feeding wounds

**Symptomatology**

- Irregular feeding holes on leaves
- Skeletonization (veins remain intact)
- Presence of frass pellets
- Damaged flower buds and young shoots
- Severe cases show bare plants

**Identification features**

- Larvae visible on plants, especially during evening or night
- Characteristic body markings and stripes
- Hairy caterpillars covered with dense setae
- Adults are dull colored moths

**Environmental influence on disease and pest incidence**

| Factor | Collar rot | Caterpillars |
|---|---|---|
| Temperature | High (25–35°C) | Moderate to high |
| Humidity | High | Moderate |
| Soil condition | Poor drainage favors disease | Not soil dependent |
| Cropping system | Continuous cropping increases risk | Mixed cropping may reduce infestation |

**Advanced diagnostic approaches**

- Molecular techniques (PCR) for pathogen detection
- Light traps for monitoring moth population
- Field scouting for early larval detection
- Soil testing for pathogen presence

**Management of Leaf-Eating Caterpillars**

Caterpillars are controlled by regular scouting, handpicking and removing egg masses. Biological methods like *Bacillus thuringiensis (Bt)* and neem-based products are eco-friendly options. Severe infestations can be managed using insecticides like spinosad or emamectin benzoate.

**Economic impact**

- Collar rot can cause up to 50–70% plant mortality
- Caterpillar infestation leads to severe yield and quality losses
- Increased cost of plant protection measures
- Reduced market value due to poor flower quality

**Integrated perspective**

Both problems differ fundamentally:

- Collar rot is soil borne and systemic
- Caterpillars are external feeders and mobile pests

Understanding these differences is crucial for:

- Accurate diagnosis
- Timely intervention
- Sustainable crop management

**Conclusion**

Collar rot and leaf eating caterpillars are among the most significant biotic stresses affecting goldenrod cultivation. Collar rot is characterized by basal stem decay, fungal growth,ill and plant wilting, whereas caterpillar infestation results in defoliation and visible feeding damage. Detailed knowledge of their biology, symptoms and environmental requirements enables precise identification and forms the basis for effective management strategies.

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ISSN : 2583-0910
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Peer reviewed
monthly newsletter

Article ID : 06/VI/16/0626

# THE HIDDEN PARTNERSHIP: OBLIGATE MUTUALISM BETWEEN FIG AND FIG WASP

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## Abstract

The obligate mutualism between fig trees and fig wasps represents one of the most remarkable examples of coevolution in nature. In this highly specialized relationship, both organisms depend entirely on each other for survival and reproduction. Fig trees provide food, shelter, and a breeding site for fig wasps, while fig wasps act as the exclusive pollinators of fig flowers. Unlike most flowering plants, fig flowers are enclosed within a unique structure called a syconium, making pollination possible only through the entry of a female fig wasp via a narrow opening known as the ostiole. During this process, the wasp pollinates the flowers and lays eggs, allowing both seed formation and wasp development to occur within the fig. The life cycle of the fig wasp is closely synchronized with the reproductive cycle of the fig tree, demonstrating a remarkable evolutionary partnership developed over millions of years. Each fig species is generally associated with a specific wasp species, highlighting the precision of this biological interaction. Beyond their mutual dependence, fig trees also play an important ecological role as keystone species, providing a critical food source for many animals such as birds, bats, monkeys, and insects. The fig–fig wasp mutualism therefore not only ensures the survival of the two species involved but also contributes significantly to ecosystem stability and biodiversity. This intricate partnership illustrates the complexity of ecological relationships and emphasizes the importance of conserving such interactions in natural ecosystems.

**Keywords**: Obligate mutualism, Fig tree (*Ficus*), Fig wasp, Coevolution, Pollination

## Introduction

Nature is full of fascinating partnerships where different organisms depend on each other to survive. One of the most remarkable examples of such cooperation is the relationship between the fig tree and the fig wasp. This partnership is known as obligate mutualism, meaning that both species depend completely on each other for survival and reproduction. Without fig wasps, fig trees cannot produce seeds, and without fig trees, fig wasps cannot reproduce. This tiny insect and the tree have developed a complex relationship over millions of years of evolution. Their interaction is so specialized that each species of fig tree usually has its own unique species of fig wasp. Although the wasp is extremely small—often only a few millimeters long—it plays a crucial role in the life cycle of the fig tree and in maintaining ecological balance in many tropical ecosystems.

**What is Obligate Mutualism?**

Mutualism is a biological interaction in which both organisms benefit from the relationship. However, obligate mutualism is a more extreme form of mutualism in which the two species cannot survive or reproduce without each other.

In the case of figs and fig wasps:

- The fig tree provides food, shelter, and a place for the wasp to lay eggs.
- The fig wasp pollinates the fig flowers, allowing the tree to reproduce.

Because both partners rely completely on each other, their life cycles are closely synchronized. If one partner disappears, the other cannot continue its life cycle.

**The Fig Tree: A Unique Flowering System**

Fig trees belong to the genus *Ficus*, which includes more than 750 species worldwide. They are commonly found in tropical and subtropical regions. Many fig species are considered keystone species because they provide food for birds, bats, monkeys, and other wildlife throughout the year. Unlike most plants, fig trees do not display their flowers openly. Instead, the flowers are hidden inside a special structure called a syconium, which looks like a fruit. What we commonly call a “fig fruit” is actually a hollow structure lined with hundreds of tiny flowers on the inside. Because the flowers are enclosed, normal pollinators such as bees or butterflies cannot reach them. This is where the fig wasp plays a vital role.

**The Fig Wasp: A Specialized Pollinator**

Fig wasps (*Blastophaga psens*) are tiny insects belonging to the family agaonidae. These insects are specifically adapted to pollinate fig trees. Each fig species usually has its own specialized fig wasp species that can pollinate only that particular fig. Female fig wasps are responsible for pollination. They carry pollen from the fig where they were born to another fig tree where they reproduce. Their bodies are specially adapted to enter the fig through a narrow opening called the ostiole. This opening is extremely small and often damages the wasp's wings and antennae as she squeezes through. In many cases, the female wasp cannot leave the fig once she enters it.

**The Life Cycle of the Fig–Fig Wasp Relationship**

The life cycle of the fig and fig wasp is one of the most extraordinary examples of coevolution in nature.

**1. Entry into the Fig**

A female fig wasp carrying pollen searches for a young fig that is ready for pollination. She enters the fig through the ostiole, forcing her way inside. During this process, her wings and antennae often break off, trapping her inside the fig permanently.

**2. Pollination and Egg Laying**

Once inside, the female wasp deposits pollen onto the tiny flowers inside the fig. This pollination allows the fig flowers to develop into seeds. At the same time, the wasp lays her eggs inside some of the flowers. These flowers develop into small chambers called galls, where the larvae grow.

**3. Development of Wasp Larvae**

The eggs hatch into larvae that feed safely inside the fig. As the larvae grow, they complete their development within the protective environment of the fig.

**4. Mating Inside the Fig**

Male wasps emerge first. They mate with the female wasps while still inside the fig. After mating, the male wasps chew an exit tunnel through the fig wall. Interestingly, male wasps never leave the fig. After completing their role in reproduction, they die inside the fig.

### 5. Female Wasps Carry Pollen

Female wasps collect pollen from the fig before leaving through the tunnel created by the males. Once they exit, they fly away in search of another young fig where they can repeat the cycle.

### Coevolution between Fig and Fig Wasp

The relationship between fig trees and fig wasps is an excellent example of coevolution, where two species evolve together over long period of time and over millions of years. Fig trees developed enclosed flowers that require specialized pollinators. Fig wasps evolved specialized body structures and behaviors to enter figs and pollinate them. Because of this tight evolutionary relationship, many fig species are pollinated by only one specific wasp species. This extreme specialization makes the relationship one of the most precise examples of mutual dependence in nature.

### Ecological Importance of Fig Trees

Fig trees play a vital role in maintaining biodiversity in tropical ecosystems. They produce fruits at different times of the year, providing food when other fruits are scarce. Many animals depend on figs, including Birds**,** Monkeys**,** Bats**,** Squirrels and Insects. Because of this, figs are often referred to as keystone species, meaning that many organisms rely on them for survival. Without figs, entire food webs could be disrupted. The presence of fig wasps ensures that fig trees continue to reproduce and produce fruits, supporting the ecosystem.

### A Remarkable Balance of Life

One fascinating aspect of the fig–fig wasp relationship is the delicate balance between cooperation and conflict. While the wasp helps pollinate the fig, it also lays eggs inside some of the flowers, which prevents those flowers from becoming seeds. However, the fig tree controls the number of eggs the wasp can lay. Some flowers develop into seeds instead of wasp larvae, ensuring the tree can still reproduce. This balance allows both species to benefit without one completely dominating the other.

### Conclusion

The relationship between fig trees and fig wasps is one of the most extraordinary examples of obligate mutualism in nature. These two organisms depend completely on each other for survival and reproduction, demonstrating the intricate connections that exist within ecosystems. Through millions of years of coevolution, fig trees have developed specialized flowers hidden within the syconium, while fig wasps have evolved unique behaviors and physical adaptations to pollinate them. This remarkable partnership not only ensures the survival of both species but also supports a wide range of wildlife that depend on figs as a food source. The fig–fig wasp interaction reminds us that even the smallest creatures can play an essential role in maintaining ecological balance. Understanding such relationships helps scientists appreciate the complexity of nature and highlights the importance of conserving biodiversity.

ISSN : 2583-0910
**Agri-India TODAY**
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Peer reviewed
monthly newsletter

Article ID : 06/VI/17/0626

# INTEGRATED WATER MANAGEMENT IN INDIAN AGRICULTURE: PRINCIPLES, PRACTICES, AND SUSTAINABLE IRRIGATION STRATEGIES FOR ENHANCED PRODUCTIVITY

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## Abstract

Water is a critical natural resource that underpins agricultural productivity, food security, and rural livelihoods, particularly in agrarian economies like India. Efficient water management has become increasingly important due to rapid population growth, climate variability, declining groundwater levels, and uneven distribution of water resources. This research article provides a comprehensive analysis of water management in agriculture, focusing on irrigation principles, water resource development, irrigation requirements, scheduling techniques, and modern irrigation methods. The study examines the evolution and current status of irrigation infrastructure in India, highlighting the role of major, medium, and minor irrigation projects. It also explores crop-specific water requirements for key agricultural crops such as rice, wheat, maize, groundnut, and sugarcane, emphasizing the need for precise irrigation scheduling based on soil moisture, climatic conditions, and crop growth stages. Further, the article discusses different irrigation methods, including surface, sprinkler, and drip irrigation, along with techniques for measuring irrigation water and improving application and distribution efficiencies. Special attention is given to conjunctive use of surface and groundwater resources to optimize water availability and sustainability.

Water quality issues, including salinity and alkalinity, and their management strategies are also analyzed. Additionally, agricultural drainage systems are discussed as essential components for maintaining soil health and preventing waterlogging. The paper concludes that integrated water management approaches combining scientific irrigation scheduling, efficient water use technologies, and policy support are essential for achieving sustainable agricultural development. Adoption of modern irrigation practices, along with farmer awareness and institutional support, can significantly improve water use efficiency and ensure long-term sustainability of water resources in Indian agriculture.

**Keywords :** Water management, Irrigation principles, Irrigation scheduling, Water use efficiency, Conjunctive use, Irrigation methods, Agricultural drainage, Water quality, Crop water requirement, Sustainable agriculture, Groundwater management, Surface irrigation, Drip irrigation, Sprinkler irrigation, Indian agriculture

## Introduction

Water is the backbone of agriculture and plays a vital role in ensuring food security and economic stability. In India, agriculture consumes nearly 80% of the total available freshwater resources. However, increasing water scarcity, erratic rainfall patterns, and over-exploitation of groundwater have created serious challenges for sustainable agricultural development. Efficient water management is therefore essential to maximize crop productivity while conserving water resources. Integrated water management involves the judicious use of available water resources through scientific irrigation practices, efficient distribution systems, and proper drainage mechanisms. This paper aims to explore the principles and practices of water management in agriculture, focusing on irrigation systems, crop water requirements, and sustainability approaches.

### Principles of Irrigation

Irrigation refers to the artificial application of water to soil to meet crop water requirements. The basic principles of irrigation include timely application, uniform distribution, adequate quantity, and minimal losses.

The principle of optimum water supply ensures that crops receive sufficient moisture without wastage. Uniform distribution ensures that water reaches all parts of the field evenly, preventing under-irrigation or over-irrigation. Another important principle is efficiency, which emphasizes minimizing losses due to evaporation, runoff, and deep percolation.

Irrigation must also be economically viable and environmentally sustainable. Over-irrigation can lead to waterlogging and soil salinity, while under-irrigation reduces crop yields. Therefore, proper planning and management are essential to balance crop needs with resource conservation.

### Water Resources and Irrigation Development in India

India possesses diverse water resources, including rivers, lakes, reservoirs, and groundwater aquifers. Major river systems such as the Ganga, Brahmaputra, and Godavari support extensive irrigation networks. Irrigation development in India has evolved through large-scale projects such as dams and canals, as well as small-scale systems like tube wells and tanks. The Green Revolution significantly increased irrigation coverage, leading to higher agricultural productivity. However, regional disparities exist, with states like Punjab and Haryana having high irrigation coverage, while rainfed regions face water scarcity. Groundwater exploitation has increased rapidly, raising concerns about sustainability. Government initiatives such as the Pradhan Mantri Krishi Sinchai Yojana (PMKSY) aim to enhance irrigation efficiency and expand coverage through micro-irrigation technologies.

### Water and Irrigation Requirements

Crop water requirement refers to the total amount of water needed for crop growth, including evapotranspiration and other losses. Factors affecting water requirements include climate, soil type, crop variety, and growth stage. Different crops have varying water needs. For instance, rice requires standing water conditions, while wheat needs moderate irrigation. Understanding crop water requirements helps in optimizing irrigation scheduling and improving water use efficiency. Irrigation requirement is calculated by considering effective rainfall and soil moisture availability. Accurate estimation prevents overuse or underuse of water resources.

### Concepts and Approaches of Irrigation Scheduling

Irrigation scheduling involves determining the timing and quantity of water application. It is crucial for efficient water use and maximizing crop yields. Approaches include soil-based methods, climate-based methods, and crop-based indicators. Soil moisture sensors and evapotranspiration models are commonly used tools. Modern technologies such as remote sensing and automated irrigation systems have improved scheduling accuracy. Proper scheduling reduces water wastage and enhances productivity.

### Methods of Irrigation

Irrigation methods can be broadly classified into surface, sprinkler, and drip irrigation.

- **Surface irrigation** includes flood, basin, and furrow methods. It is widely used but less efficient.

- **Sprinkler irrigation** simulates rainfall and is suitable for uneven terrain.
- **Drip irrigation** delivers water directly to plant roots, minimizing losses and improving efficiency.

Micro-irrigation systems are gaining popularity due to their water-saving potential and suitability for modern agriculture.

**Measurement of Irrigation Water**

Accurate measurement of irrigation water is a fundamental component of efficient water management in agriculture. It enables farmers, irrigation engineers, and policymakers to assess water usage, minimize wastage, and optimize irrigation scheduling. Measurement ensures that water is applied according to crop requirements, thereby improving water productivity and sustainability. Several methods are used for measuring irrigation water. Volumetric measurement involves calculating the volume of water delivered over time using containers or calibrated tanks. This method is simple and suitable for small-scale irrigation systems. Flow measurement devices, such as flow meters, are widely used in modern irrigation systems. These devices provide precise data on the rate of water flow through pipes and channels, allowing real-time monitoring. Another commonly used method is the use of weirs and flumes, which measure water flow in open channels. Structures such as rectangular weirs and V-notch weirs help determine discharge based on water height. Similarly, Parshall flumes are widely used due to their accuracy and low maintenance requirements. Measurement of irrigation water is crucial for improving water use efficiency. It helps in identifying losses due to seepage, evaporation, or leakage in canals and pipelines. Accurate data also supports equitable distribution of water among farmers, reducing conflicts in water-scarce regions. Furthermore, measurement plays a key role in implementing water pricing policies and promoting accountability in water use. With advancements in technology, tools such as remote sensing, IoT-based sensors, and automated irrigation systems are increasingly being used to monitor water usage. In conclusion, proper measurement of irrigation water is essential for sustainable agriculture. It enhances decision-making, improves efficiency, and ensures optimal utilization of limited water resources.

**Application, Distribution, and Use Efficiencies**

Water use efficiency is a critical parameter in evaluating the performance of irrigation systems. It refers to how effectively water is applied, distributed, and utilized by crops. Efficient water use is essential for maximizing crop productivity while conserving limited water resources.

- **Application efficiency** refers to the proportion of water applied to the field that is actually stored in the root zone of crops. Losses may occur due to evaporation, runoff, or deep percolation. Improving application efficiency involves adopting techniques such as drip irrigation, proper scheduling, and controlled water application.
- **Distribution efficiency** measures how uniformly water is distributed across the field. Uneven distribution can lead to over-irrigation in some areas and under-irrigation in others, affecting crop growth and yield. Land leveling and proper design of irrigation systems help improve distribution efficiency.
- **Water use efficiency (WUE)** is the ratio of crop yield to the amount of water used. It indicates how effectively crops convert water into biomass or yield. High WUE is achieved through improved irrigation practices, better crop varieties, and efficient nutrient management.

Several strategies can enhance irrigation efficiency. These include laser land leveling, which ensures uniform water distribution, and micro-irrigation systems such as drip and sprinkler irrigation, which reduce water losses. Additionally, lining of canals and pipelines helps minimize conveyance losses. Efficient water management not only conserves water but also reduces energy consumption and input costs. It contributes to sustainable agriculture by maintaining soil health and preventing problems such as waterlogging and salinity.

In conclusion, improving application, distribution, and use efficiencies is essential for achieving higher productivity with limited water resources. Adoption of modern technologies and scientific management practices can significantly enhance irrigation performance.

### Conjunctive Use of Water

Conjunctive use of water refers to the coordinated and combined use of surface water and groundwater resources for irrigation. This approach aims to optimize water availability, improve efficiency, and ensure sustainability of water resources. In many regions, reliance on a single source of water—either surface water or groundwater—can lead to problems. Excessive use of groundwater may result in depletion of aquifers, while over-dependence on surface water may lead to inefficient utilization and waterlogging. Conjunctive use addresses these issues by integrating both sources. For example, during monsoon seasons, surface water from rivers and reservoirs can be used extensively, allowing groundwater reserves to recharge. In dry seasons, groundwater can supplement irrigation needs when surface water availability is low. This balanced approach helps maintain groundwater levels and ensures a continuous supply of water. Conjunctive use also plays a significant role in improving water quality. In areas where groundwater is saline or alkaline, mixing it with good-quality surface water can reduce its harmful effects on crops and soil. This blending technique enhances the usability of marginal water resources. Moreover, conjunctive use contributes to preventing waterlogging and salinity. In canal-irrigated areas, excessive seepage can raise the water table, leading to waterlogging. Pumping groundwater in such areas helps lower the water table and maintain soil health. The implementation of conjunctive use requires proper planning, infrastructure, and monitoring. It involves the integration of irrigation systems, groundwater extraction technologies, and policy support. In conclusion, conjunctive use of water is a sustainable approach that ensures efficient utilization of available resources. It enhances water security, improves agricultural productivity, and supports long-term environmental sustainability.

### Irrigation Water Quality and Its Management

Water quality is a critical factor influencing agricultural productivity and soil health. Irrigation water may contain dissolved salts, minerals, and other substances that can affect crop growth and soil properties. Poor-quality water can lead to problems such as salinity, alkalinity, and toxicity. Salinity occurs when water contains high concentrations of soluble salts, which accumulate in the soil and hinder plant growth. Alkalinity, on the other hand, is caused by high levels of sodium, leading to soil structure degradation and reduced permeability. These conditions adversely affect crop yield and soil fertility.

To manage water quality issues, several strategies are employed. Leaching involves applying excess water to flush out salts from the root zone. Application of gypsum helps neutralize sodium ions and improve soil structure in alkaline soils. Another approach is blending, where poor-quality water is mixed with good-quality water to reduce its harmful effects. Selection of salt-tolerant crop varieties is also an effective strategy for managing poor-quality irrigation water. Crops such as barley and certain varieties of wheat can tolerate higher salinity levels. Additionally, proper drainage systems are essential to prevent the accumulation of salts in the soil. Regular monitoring of water quality is crucial for effective management. Parameters such as electrical conductivity (EC), pH, and sodium adsorption ratio (SAR) are commonly used to assess water quality. Modern technologies enable real-time monitoring and analysis, helping farmers make informed decisions. In conclusion, maintaining irrigation water quality is essential for sustainable agriculture. Proper management practices can mitigate the adverse effects of poor-quality water, ensuring healthy soil and improved crop productivity.

### Water Management in Major Field Crops

Efficient water management is essential for maximizing the productivity of major field crops. Different crops have varying water requirements and respond differently to irrigation practices. Understanding crop-specific water needs helps in optimizing irrigation and improving yields.

- **Rice** is a water-intensive crop that requires continuous flooding during most of its growth stages. However, techniques such as alternate wetting and drying (AWD) can reduce water use without affecting yield.
- **Wheat** requires moderate irrigation and is sensitive to water stress during critical stages such as tillering, flowering, and grain filling. Proper timing of irrigation is essential for achieving high yields.
- **Maize** is highly sensitive to moisture stress, particularly during tasseling and silking stages. Adequate irrigation during these stages is crucial for grain development.
- **Groundnut** requires well-drained soil and is sensitive to waterlogging. Excess water can damage the crop, while insufficient water affects pod development. Controlled irrigation is therefore necessary.
- **Sugarcane** is a high water-demand crop that requires frequent irrigation throughout its long growing period. Efficient methods such as drip irrigation can significantly reduce water use and improve yield.

Adopting modern irrigation techniques, such as drip and sprinkler systems, can improve water use efficiency in all these crops. Additionally, proper scheduling based on soil moisture and climatic conditions ensures optimal water application. In conclusion, crop-specific water management practices are essential for achieving higher productivity and resource conservation. Efficient use of water not only enhances yields but also contributes to sustainable agriculture.

### Agricultural Drainage

Agricultural drainage is an essential component of water management that involves the removal of excess water from the soil. Proper drainage ensures optimal soil moisture conditions, promotes root growth, and prevents soil degradation. Excess water in the soil can lead to waterlogging**,** which reduces oxygen availability to plant roots and inhibits growth. It can also cause the accumulation of salts, leading to soil salinity. Therefore, effective drainage systems are necessary to maintain soil health and productivity. There are two main types of drainage systems: surface drainage and subsurface drainage. Surface drainage involves the removal of excess water from the soil surface through channels, ditches, or slopes. It is commonly used in areas with heavy rainfall or poor infiltration. Subsurface drainage involves the removal of water from below the soil surface using pipes or tiles. This method is effective in controlling the water table and preventing waterlogging in irrigated areas. Proper design and maintenance of drainage systems are crucial for their effectiveness. Factors such as soil type, topography, and climate must be considered during planning. Drainage also plays a key role in managing soil salinity. By removing excess water and salts, it helps maintain soil fertility and improves crop yields. In conclusion, agricultural drainage is vital for sustainable water management. It prevents waterlogging, improves soil conditions, and enhances agricultural productivity.

**Conclusion**

Sustainable water management is a cornerstone of modern agriculture, particularly in water-scarce regions like India. With increasing population pressure, climate variability, and declining water resources, efficient utilization of water has become more important than ever.

This study highlights the importance of integrating various aspects of water management, including accurate measurement, efficient application, proper distribution, and effective use of water resources. Techniques such as irrigation scheduling, micro-irrigation, and conjunctive use of water can significantly improve water use efficiency and agricultural productivity. Water quality management and agricultural drainage are equally important components of sustainable water management. Addressing issues such as salinity, alkalinity, and waterlogging ensures long-term soil health and productivity. The adoption of modern technologies, such as remote sensing, IoT-based irrigation systems, and automated water management tools, can revolutionize agricultural practices. These innovations enable precise monitoring and efficient use of water resources. Policy support and farmer awareness are also critical for successful implementation. Government initiatives aimed at improving irrigation infrastructure and promoting efficient water use play a vital role in achieving sustainability goals. In conclusion, integrated water management approaches are essential for ensuring food security, environmental sustainability, and economic development. By adopting scientific and sustainable practices, agriculture can meet the growing demand for food while conserving precious water resources for future generations.

ISSN : 2583-0910
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Peer reviewed
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Article ID : 06/VI/18/0626

# RUMEN-DERIVED GREENHOUSE GAS EMISSIONS AND NUTRITIONAL MITIGATION STRATEGIES

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## Abstract

Ruminant livestock contribute significantly to greenhouse gas emissions, particularly methane ($CH_4$), which is produced during rumen fermentation by methanogenic archaea. This process not only impacts the environment but also results in a loss of 2–12% of dietary energy. Methanogenesis maintains rumen function by regulating hydrogen balance, but reducing methane can improve feed efficiency and productivity. Various mitigation strategies have been explored. Feed manipulation, such as improving forage quality and increasing concentrate levels, shifts fermentation toward propionate production, reducing hydrogen availability. Feed additives, including ionophores, essential oils, plant extracts, biochar, and seaweeds, can inhibit methanogens or alter rumen microbial activity. Direct-fed microbials, particularly propionic acid bacteria, further reduce methane by redirecting hydrogen to beneficial pathways. An integrated approach combining these strategies is essential for sustainable and efficient ruminant production.

## Introduction

Rising global temperatures have intensified concern over the greenhouse effect, primarily driven by gases such as carbon dioxide ($CO_2$), methane ($CH_4$), and nitrous oxide ($N_2O$). These gases trap heat in the atmosphere, contributing to climate change with significant implications for ecosystems, livestock, and human well-being. Among them, methane is particularly potent, possessing over 21 times the global warming potential of $CO_2$ and accounting for a substantial loss (2–12%) of gross energy intake in ruminants through enteric fermentation. Agriculture contributes significantly to methane emissions, with enteric fermentation, rice cultivation, and manure management accounting for nearly 40% of total agricultural $CH_4$ output. Ruminant livestock especially cattle are the major contributors, responsible for approximately 72% of emissions, while buffaloes and small ruminants contribute comparatively less. Despite its high warming potential, methane has a relatively short atmospheric lifespan (~8.6 years), making it a critical target for short-term climate mitigation. Reducing enteric methane emissions offers dual benefits: improving feed energy efficiency and enhancing environmental sustainability. While strategies such as culling low-producing animals are practiced in developed countries, such approaches are often impractical in developing regions due to socio-economic and cultural constraints. Therefore, emphasis is placed on developing cost-effective and sustainable mitigation strategies that balance productivity with environmental responsibility.

## Methanogenesis in Ruminant Animals

The rumen hosts a complex anaerobic microbial ecosystem comprising bacteria, protozoa, methanogenic archaea, and fungi that collectively degrade dietary macromolecules. Carbohydrate fermentation produces short-chain volatile fatty acids (SVFAs), primarily acetate (≈65%), propionate (≈20%), and butyrate (≈15%) which supply up to 80% of the host's energy requirements. However, this process also generates metabolic hydrogen ($H_2$), which must be removed to sustain efficient fermentation. Methanogenesis serves as the principal hydrogen disposal pathway in the rumen. Methanogenic archaea, predominantly *Methanobrevibacter* spp., utilize hydrogen to reduce carbon dioxide to methane via hydrogenotrophic pathways, accounting for approximately 82% of total ruminal methane production. By maintaining low hydrogen partial pressure, methanogens facilitate optimal microbial activity and prevent inhibition of carbohydrate oxidation. Interspecies hydrogen transfer between methanogens and hydrogen-producing microbes (bacteria, protozoa, and fungi) plays a critical role in stabilizing rumen fermentation. The balance between hydrogen production and utilization regulates metabolic flux, including competition with alternative pathways such as reductive acetogenesis. Although methanogenesis is essential for rumen function, it represents a significant loss of dietary energy and contributes substantially to greenhouse gas emissions from ruminant systems.

## Mitigation Strategies

### Mitigation through Feed Manipulation

Dietary manipulation is a cost-effective strategy to reduce enteric methane emissions (up to ~70%). Improving forage quality enhances digestibility and shifts fermentation toward propionate production, reducing hydrogen ($H_2$) availability for methanogenesis. Increasing the concentrate-to-forage ratio (35–60%) further lowers methane output but may increase the risk of Subacute Ruminal Acidosis if not properly balanced.

### Mitigation through Feed Additives

Feed additives mitigate methane by inhibiting methanogens or altering rumen fermentation.

- **Ionophores:** Improve feed efficiency and reduce methane by shifting fermentation toward propionate and suppressing hydrogen-producing Gram-positive bacteria.
- **Essential Oils and Plant Extracts:** Compounds such as saponins and tannins reduce methane (≈28–30%) by inhibiting methanogens and protozoa.
- **Other Additives:** Biochar, seaweeds, and prebiotics (e.g., chitosan, inulin, yeast) show promising anti-methanogenic effects, though large-scale application requires further

### Mitigation through Direct-Fed Microbials (DFMs)/Probiotics

Direct-fed microbials (DFMs) are live microbial cultures. They may consist of single or mixed strains. These microbes promote beneficial rumen microflora when fed to animals. DFMs improve rumen fermentation and animal performance. They also influence hydrogen utilization in the rumen. Several rumen microbes compete with methanogens for hydrogen. They promote alternative pathways such as propionogenesis, acetogenesis, and nitrate/nitrite or sulfate reduction. These pathways act as alternative hydrogen ($H_2$) sinks. As a result, hydrogen is redirected toward volatile fatty acid (VFA) production. This reduces its availability for methanogenesis.

### Propionic Acid Bacteria (PAB)

Direct-fed microbials (DFMs) are live microbial cultures that enhance rumen function by modulating microbial populations and fermentation pathways. They improve animal performance and reduce methane emissions by redirecting hydrogen ($H_2$) toward alternative metabolic pathways such as propionogenesis, acetogenesis, and nitrate or sulfate reduction, thereby limiting substrate availability for methanogenesis.

### Propionic Acid Bacteria (PAB)

Propionibacteria are Gram-positive rumen inhabitants that contribute to propionate production via the succinate and acrylate pathways, utilizing hydrogen in the process. Enhanced propionate formation acts as an alternative hydrogen sink, reducing methane production. Key strains, including

*Propionibacterium acidipropionici*, *P. freudenreichii*, and *P. jensenii*, have demonstrated methane mitigation potential in both in vitro and in vivo studies.

**Methane-Oxidizing Bacteria (MOB)**

Methane-oxidizing bacteria utilize methane as a carbon and energy source, converting it to methanol via methane monooxygenase and further to formaldehyde for biomass synthesis. Although they present a promising biological approach to methane mitigation, their application as probiotics in ruminants remains limited, requiring further isolation, characterization, and in vivo validation.

## Conclusion

Enteric methane production is an unavoidable outcome of rumen fermentation, contributing to greenhouse gas emissions and energy loss. Strategies such as dietary manipulation, feed additives, and direct-fed microbials can reduce methane by redirecting hydrogen toward more efficient pathways. However, no single method is sufficient. An integrated approach combining nutritional and microbial interventions is essential to achieve sustainable methane mitigation while maintaining animal health and productivity.

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ISSN : 2583-0910
Agri-India TODAY
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Peer reviewed
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Article ID : 06/VI/19/0626

# ADVANCING SUSTAINABLE AQUACULTURE AND FISHERIES THROUGH MICROBIAL ENZYMES AND BIOMOLECULES

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## Abstract

Disease outbreaks, environmental degradation, and the enormous production of organic waste are just a few of the serious issues brought about by the fast growth of the world's fisheries and aquaculture industries. Innovative and environmentally friendly approaches are desperately needed to guarantee the long-term sustainability of aquatic resources. The transformative potential of microbial enzymes and biomolecules in contemporary fisheries resource management is examined in this article. We emphasize the use of particular enzymes, like lipases, proteases, and chitinases, to turn waste from seafood processing into valuable bioproducts. Additionally, it is discussed how microbial biomolecules, such as probiotics and antimicrobial peptides, can improve aquaculture disease resistance and take the place of synthetic antibiotics. The fishing industry can move toward a sustainable, circular economy model by incorporating these biotechnological tools.

**Keywords:** Microbial enzymes, Biomolecules, Fisheries management, Aquaculture sustainability, Waste valorization

## Introduction

Both capture fisheries and aquaculture are rapidly intensifying due to the unprecedented levels of global demand for seafood. Global food security depends on this growth, but it has also created serious ecological and environmental problems. The delicate balance of aquatic ecosystems is threatened by overfishing, habitat destruction, the spread of aquatic diseases, and the buildup of biological waste from seafood processing. As a result, a paradigm shift in fisheries resource management is taking place, with sustainable, bio-based solutions replacing purely extractive methods. Microbial enzymes and biomolecules are among the most promising tools in this transition.

Microorganisms are a huge and mostly unexplored source of biocatalysts and bioactive compounds, especially those found in marine environments. Proteases, lipases, amylases, and chitinases are examples of microbial enzymes, and probiotics, biosurfactants, and antimicrobial peptides are examples of biomolecules that provide highly specific, effective, and eco-friendly substitutes for conventional chemical processes. These biological tools are being used in three main areas of fisheries management: bioremediation of aquatic environments, disease control and nutritional improvement in aquaculture, and the value-adding of waste from seafood processing. An extensive summary of the use of microbial biotechnology to support sustainable fisheries resource management is given in this article.

## Microbial biomolecules in aquaculture health and nutrition

Disease outbreaks and suboptimal feed conversion ratios present significant challenges in aquaculture, resulting in substantial economic losses and resource depletion. Traditionally, these issues were addressed through extensive use of synthetic antibiotics and chemical treatments, which inadvertently contributed to the emergence of antimicrobial resistance (AMR) and environmental toxicity. Microbial biomolecules present a sustainable alternative to these conventional approaches.

**Probiotics and Antimicrobial Peptides**

The use of probiotics-live microorganisms that provide health benefits to the host-has emerged as a fundamental strategy for sustainable aquaculture management. Microbial strains from genera such as Bacillus, Lactobacillus, and Pseudomonas produce various biomolecules that enhance the intestinal microbiome of farmed fish and crustaceans. These probiotics operate through competitive exclusion, effectively outcompeting pathogenic bacteria for nutrients and adhesion sites in the host's gut.

Additionally, marine microbes are significant producers of antimicrobial peptides (AMPs). These small, bioactive molecules demonstrate broad-spectrum activity against bacterial, viral, and fungal pathogens by disrupting their cell membranes. By integrating microbial AMPs into aquaculture systems, farm managers can substantially decrease reliance on traditional antibiotics, thereby reducing the risk of AMR and ensuring the production of safer seafood for human consumption (figure1).

**Enzymatic feed additives**

The sustainability of fisheries is closely linked to the effectiveness of aquaculture feeds. As the industry transitions from wild-caught fishmeal to plant-based protein sources, new nutritional challenges arise. Plant-derived ingredients may contain anti-nutritional factors, such as phytic acid, which hinder fish from absorbing vital minerals like phosphorus. To address this issue, microbial enzymes, particularly phytases, are commonly incorporated into aquafeeds to degrade phytic acid. This biomolecular approach enhances nutrient absorption and growth rates in fish while significantly decreasing the amount of unabsorbed phosphorus released into the water. Furthermore, microbial proteases and lipases are employed to pre-digest complex proteins and fats in feed formulations, thereby improving overall feed conversion ratios. By optimizing nutrient utilization, enzymatic additives alleviate the biological pressure on wild fish stocks used for fishmeal and reduce the organic load in aquaculture effluents.

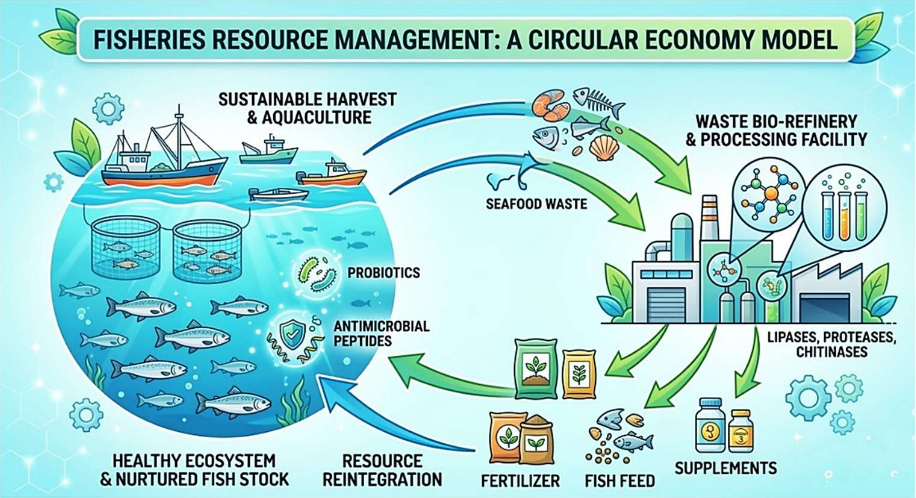

**Figure 1**. *A circular bioeconomy model for sustainable fisheries resource management utilizing microbial bioprocessing.*

### Water quality management and bioremediation

Ensuring optimal water quality is essential for effective fisheries and aquaculture management. Intensive farming practices frequently result in the buildup of uneaten feed, fecal matter, and harmful nitrogenous compounds, including ammonia and nitrites. If not properly managed, these pollutants can lead to eutrophication, algal blooms, and significant fish mortality events.

### Enzymatic degradation of aquatic pollutants

Bioremediation through the use of microbial enzymes offers an environmentally sustainable method for preserving water quality. Specialized groups of nitrifying and denitrifying bacteria are utilized in aquaculture ponds and biofilters to transform highly toxic ammonia into less harmful nitrates and, ultimately, nitrogen gas. In addition to nitrogen management, microbial enzymes are essential for the degradation of accumulated organic sludge. Extracellular enzymes, including cellulases, amylases, and proteases, produced by naturally occurring or introduced microbes, break down complex organic material into simpler, soluble compounds. Furthermore, biosurfactants-amphiphilic biomolecules generated by microbes-are increasingly recognized in fisheries management for their effectiveness in remediating oil spills and hydrocarbon contamination in fishing harbors and coastal waters. These biomolecules enhance the bioavailability of hydrophobic pollutants, enabling native microorganisms to degrade them more effectively.

### Valorization of seafood processing waste

Capture fisheries and aquaculture produce millions of tons of biological waste each year, such as fish heads, viscera, skin, scales, and crustacean shells. Disposing of this biomass in landfills or coastal waters leads to significant environmental pollution. However, from the perspective of microbial biotechnology, this "waste" is considered a valuable source of proteins, lipids, calcium, and chitin.

### Chitin extraction using microbial chitinases

Crustacean processing waste is rich in chitin, a biopolymer with significant applications in medicine, agriculture, and wastewater treatment. Traditional methods for chitin extraction utilize harsh acids and strong bases, which pose environmental risks and can compromise the quality of the final product.

Microbial biomolecules present a sustainable, eco-friendly alternative. Lactic acid-producing bacteria can effectively demineralize crustacean shells, while microbial proteases can deproteinize the biomass. Additionally, microbial chitinases can hydrolyze the extracted chitin into chito-oligosaccharides (COS), which are valuable biomolecules known for their antioxidant, anti-inflammatory, and immune-stimulating properties. By adopting these microbial processes, fisheries managers can transform hazardous processing by-products into profitable commodities.

### Proteases in bioactive peptide generation

Crustacean processing waste contains a high concentration of chitin, a biopolymer with valuable applications in medicine, agriculture, and wastewater treatment. Conventional methods for extracting chitin typically involve harsh acids and strong bases, which can pose environmental hazards and adversely affect the quality of the final product. Studies of different publication have been concluded in the table 1. Utilizing microbial biomolecules offers a sustainable and environmentally friendly alternative. Lactic acid-producing bacteria can efficiently demineralize crustacean shells, while microbial proteases can remove proteins from the biomass. Furthermore, microbial chitinases can hydrolyze the extracted chitin into chito-oligosaccharides (COS), which possess significant antioxidant, anti-inflammatory, and immune-stimulating properties. By implementing these microbial processes, fisheries managers can convert potentially harmful processing by-products into valuable commodities.

**Table 1**: **Biotechnological interventions in fisheries: A review of recent microbial enzyme and biomolecule applications**

| **Study Focus and Key Findings** | **Author(s) & Year** |
|---|---|
| **Chitin extraction from crustacean waste:** Demonstrated that utilizing microbial chitinases effectively extracts high-quality chitin from shrimp and crab shells, significantly reducing the environmental toxicity associated with traditional chemical demineralization. | Al-Zuhair *et al*. (2020) |
| **Probiotics for disease control:** Evaluated the application of *Bacillus* and *Lactobacillus* probiotics in intensive aquaculture. The study found that these biomolecules significantly improved disease resistance by competitively excluding pathogenic *Vibrio* species in the host gut. | Defoirdt *et al*. (2021) |
| **Proteases for fish protein hydrolysates:** Investigated the enzymatic hydrolysis of fish viscera and processing by-products. They found that specific microbial proteases yielded bioactive fish protein hydrolysates (FPH) exhibiting strong antioxidant and nutritional properties suitable for aquafeeds. | Liao *et al*. (2019) |
| **Bioremediation of aquaculture effluents:** Showed that introducing specialized consortia of nitrifying bacteria and their extracellular enzymes rapidly degraded accumulated organic sludge and reduced toxic ammonia and nitrite levels in high-density farming ponds. | Martinez-Porchas *et al*. (2022) |
| **Enzymatic feed additives:** Found that incorporating microbial phytases into plant-based aquafeeds successfully broke down anti-nutritional phytic acid. This improved phosphorus absorption in farmed fish and drastically reduced nutrient pollution in water effluents. | Nayak *et al*. (2023) |
| **Antimicrobial peptides (AMPs) as alternatives to antibiotics:** Highlighted the efficacy of marine-derived microbial AMPs. The study confirmed that these biomolecules disrupt the cell membranes of aquatic pathogens, providing a viable alternative to synthetic antibiotics and mitigating antimicrobial resistance (AMR). | Smith & Brown (2021) |
| **Lipases for lipid recovery:** Studied the application of microbial lipases to process fish industry waste. The findings revealed a highly efficient recovery of omega-3 rich polyunsaturated fatty acids (PUFAs) without the thermal degradation caused by traditional rendering methods. | Vairamani *et al*. (2022) |

## Conclusion

The incorporation of microbial enzymes and biomolecules into fisheries resource management is essential for promoting ecological sustainability and economic resilience. This manuscript illustrates how these biological tools offer diverse solutions to significant industry challenges. These include substituting harmful synthetic antibiotics with microbial probiotics and antimicrobial peptides, as well as employing specific enzymes for the bioremediation of aquatic environments and the repurposing of seafood waste. Microbial biotechnology supports a circular economy. Future research should prioritize the exploration of novel marine microbes and the optimization of large-scale fermentation processes to enhance the economic accessibility of these biomolecules for fisheries managers globally. By adopting these innovations, the global fisheries sector can maintain its productivity while protecting the health of marine and freshwater ecosystems for future generations.

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ISSN : 2583-0910
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Article ID : 06/VI/20/0626

# MEDICINAL AND ECONOMIC IMPORTANCE OF *Cordyceps* IN ARUNACHAL PRADESH: BIOACTIVE PROPERTIES AND CULTIVATION PROSPECTS

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## Abstract

Cordyceps is a rare and highly valued entomopathogenic fungus widely distributed in the Himalayan region, including Arunachal Pradesh, India. It is renowned for its diverse bioactive compounds, such as cordycepin, polysaccharides, sterols and peptides, which exhibit significant pharmacological properties, including anticancer, antioxidant, anti-inflammatory, and immunomodulatory effects. Traditionally used in indigenous medicine, *Cordyceps* also holds considerable economic importance due to its high market value, often referred to as "Himalayan Gold." However, overharvesting, climate change, and illegal trade have led to a decline in natural populations. Artificial cultivation methods, including solid-state fermentation, liquid culture, and insect-based substrates, have been developed to ensure sustainable production. Additionally, its anamorphic stage, *Beauveria bassiana* is widely used as an eco-friendly bio-insecticide. This review highlights the bioactive potential, economic significance, and advances in cultivation of *Cordyceps*, emphasizing its role in sustainable agriculture and pharmaceutical development.

## Introduction

Fungi have long been recognized as valuable sources of bioactive compounds with significant pharmaceutical and industrial applications. In recent decades, considerable attention has been directed toward the in vitro cultivation of fungi to enhance the commercial production of these metabolites. Among them, species of *Cordyceps* and other entomopathogenic fungi have emerged as important research targets due to their dual significance in medicine and biological control. The ability of these fungi to produce diverse secondary metabolites with therapeutic properties, along with their potential use as biopesticides, has attracted the interest of mycologists, entomologists, and biotechnologists worldwide. Consequently, extensive studies have focused on the identification, isolation, and characterization of bioactive constituents, as well as the development of efficient cultivation techniques and clinical evaluation of selected species, particularly *Cordyceps sinensis*.

The natural occurrence of fruiting bodies in certain entomopathogenic fungi, such as *Beauveria bassiana* is relatively rare, which limits their direct utilization and necessitates the development of artificial cultivation methods. Early investigations demonstrated that fruiting bodies of *Cordyceps* species could be successfully induced under controlled conditions using organic substrates. Notably, Kobayasi (1941) first reported the successful cultivation of *Cordyceps* on rice, establishing a foundation for subsequent research. Since then, cereal-based substrates, especially rice, have been widely adopted for the in vitro production of fruiting bodies in various *Cordyceps* species. In addition to plant-derived substrates, alternative approaches involving insect hosts, such as silkworm pupae, have also been explored, providing favorable nutritional and physiological conditions for fungal growth and fruiting.

Recent advancements have further highlighted the therapeutic potential of entomopathogenic fungi. Studies have indicated that *B. bassiana* possesses anti-inflammatory properties and may play a role in regulating atopic dermatitis, suggesting its possible application as a natural therapeutic agent (Byeon et al., 2011; Wu et al., 2011). These findings have enhanced the scientific and commercial value of such fungi and have encouraged efforts toward their large-scale cultivation. Furthermore, research on fungal biology has revealed the occurrence of anamorphic compatibility through hyphal fusion under in vitro conditions, which may lead to the formation of teleomorphic stages when suitable environmental parameters—such as temperature, humidity, and pH—are maintained, similar to those found in high-altitude ecosystems. Despite these advances, there remains a need for comprehensive studies focusing on the identification, quantification, and functional evaluation of bioactive compounds responsible for the medicinal properties of *Cordyceps* and related fungi. Such investigations are essential for the development of standardized cultivation protocols and for ensuring the sustainable utilization and commercialization of these valuable biological resources.

## ***Cordyceps***

Cordyceps, commonly known as the caterpillar fungus, is a rare and highly valued entomopathogenic fungus predominantly found in the alpine regions of the Himalayas and the Qinghai–Tibetan Plateau of southwestern China. Due to its unique biological characteristics and cultural relevance, it is referred to by various local names, including "Keeda Jadi" (insect herb) in India, "Yarsagumba" (summer herb–winter worm) in Nepal, "Yartsa Guenboob" in Bhutan, "Yartsa Gunbu" in Tibet, and "Dong Chong Xia Cao" in China. Among its related taxa, *Cordyceps bassiana* (anamorph: *Beauveria bassiana*), a member of Ascomycota, is widely recognized for its broad host range and its importance in both medicinal and agricultural applications. Traditionally, *Cordyceps* has been associated with enhancing physical performance, including energy, stamina, endurance, appetite, and reproductive health, which has led to its popular designation as "Himalayan Viagra" or the "Love Flower."

The natural distribution of *Cordyceps* is largely confined to high-altitude grasslands, particularly in subtropical to temperate regions. In Arunachal Pradesh, India, it is commonly found in alpine meadows of Mechuka and Monigong (West Siang), Tuting (Upper Siang), and Taksing (Upper Subansiri), typically during the summer months from June to August. The fungus exhibits a distinctive parasitic life cycle, wherein it infects insect larvae present in the soil. Following infection, the fungal mycelium proliferates within the host, eventually leading to its mummification (Figure 1). Subsequently, a specialized reproductive structure known as a stroma develops and emerges from the insect body, usually protruding from the head region (Figure 2).

This unique host–pathogen interaction contributes significantly to the ecological and economic importance of *Cordyceps*. The fungus is widely utilized in the preparation of herbal medicines and nutraceutical products, which are commercially marketed in various forms (Figure 3). Furthermore, its anamorphic stage, represented by Beauveria bassiana, plays a crucial role in biological pest control and serves as an important source of bioactive compounds. Infection of insect hosts by this fungus, such as the banana scarring beetle, highlights its potential application as a bio-insecticide (Figure 4). The increasing global demand for *Cordyceps* underscores the need for sustainable harvesting practices and the development of efficient artificial cultivation strategies.

Figure 1. Cordyceps infected insect

Figure 2. Stromata of Cordyceps emerging from insect body

Figure 3. Commercially sold Cordyceps packet.

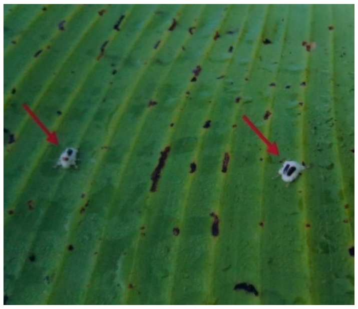

Figure 4. Beauveria bassiana infected scarring beetle of banana.

***Beauveria Bassiana*- An Anamorph of *Cordypes bassiana***

The extensive use of chemical insecticides has significantly contributed to the management of agricultural pests; however, their long-term application has led to serious challenges, including the development of insecticide resistance and adverse environmental impacts. In response to these concerns, bio-insecticides derived from entomopathogenic microorganisms have gained increasing attention as sustainable alternatives. Among the most effective biological control agents are *Metarhizium anisopliae*, *Beauveria bassiana* and *Bacillus thuringiensis*, all of which have demonstrated considerable efficacy against a wide range of insect pests.

In particular, *Beauveria bassiana*, the anamorphic (asexual) stage of *Cordyceps bassiana*, is a naturally occurring soil-borne fungus that has been widely utilized for commercial biocontrol applications. It infects insect hosts through spore attachment and cuticular penetration, ultimately leading to host mortality. Due to its effectiveness and eco-friendly nature, several commercial formulations of *B. bassiana* are available in India and are commonly used in integrated pest management programs. Biological insecticides such as *B. bassiana* offer significant advantages in terms of environmental safety and reduced risk to human health compared to conventional chemical pesticides. Furthermore, the integration of such bioagents with existing pest control strategies, including chemical insecticides or synergistic compounds, may enhance overall efficacy while minimizing resistance development. Advances in research focusing on the structural characterization of fungal toxins, their modes of action, and their impact on non-target organisms are crucial for optimizing their application. Additionally, improving toxin production through in vitro techniques could further strengthen the role of entomopathogenic fungi as reliable and sustainable tools for modern pest management.

**Artificial cultivation**

Artificial cultivation of *Cordyceps* involves diverse techniques ranging from traditional solid-state cultivation on cereal substrates to advanced submerged fermentation systems. Grain-based methods are primarily used for fruiting body production, whereas liquid fermentation is favored for rapid biomass and metabolite production. Semi-natural insect-based substrates enhance bioactive compound yield by mimicking the fungus's natural ecology. Recent technological advancements, including standardized protocols developed by research institutes such as ICAR, have enabled efficient and scalable production under controlled conditions, making *Cordyceps* cultivation commercially viable and sustainable.

**Livelihood, Medicinal Use and its Market Value**

As insect-borne mushroom, this genus has been studied for diverse medicinal use and pharmacological activities (Zhou *et al.*, 2009). In rural Tibet, it has become the most important source of earnings, rendering nearly half of the annual income of local households. The Himalayan *Ophiocordyceps* production is an important source of earning and because of its high value, inter-village conflicts have become a problem for the local government, where people being killed in some cases. The earliest record outlining the tonic properties of *C. sinensis* especially as an aphrodisiac is a 15th Century Tibetan medical.

*Cordyceps* have been a subject of curiosity for hundreds of years. They have been prized for their hidden medicinal values, especially in the Eastern Asian Society. It is widely used as a tonic and aphrodisiac. Internationally, the health efficacies of *C. sinensis* are observed and tested in asthma, allergic rhinitis, poor renal function, renal injuries by chemicals, chronic bronchitis, coughing, poor resistance of respiratory tract, regulating blood pressure (high or low blood pressure), anti-aging, weakness, the declining of sex drive, lowering raised blood lipid levels, strengthening the body's immunity, poor function of lungs and kidneys and in irregular menstruation ( Zhu *et al.,* 1998).

The genus Cordyceps is recognized for its rich repertoire of bioactive constituents that contribute to a wide spectrum of pharmacological activities. Among these, nucleosides such as cordycepin and adenosine are particularly important, exhibiting antitumor, anti-inflammatory, antimicrobial, antidiabetic, and immunomodulatory properties, along with roles in platelet aggregation inhibition and neurological regulation. Polysaccharides constitute another major class, including exopolysaccharides and acid polysaccharides, which demonstrate potent antioxidant, immunomodulatory, and anticancer activities. Specific fractions such as CPS-1 and CME-1 are known for their antioxidant potential, whereas CPS-2 and mannose-rich glucans exhibit cytotoxic and antiproliferative effects. Additionally, cordyglucans and related compounds contribute to tumor suppression, while cordycepic acid (D-mannitol) provides diuretic and free radical scavenging benefits. Sterols such as ergosterol and β-sitosterol further enhance the therapeutic profile by offering antimicrobial, antiviral, cardioprotective, and anticancer effects, alongside supporting bone health and immune regulation. Proteinaceous components, including enzymes and peptides, also play significant roles; for instance, fibrinolytic proteins aid in thrombolysis, cordymin exhibits antidiabetic and antifungal activities, and several peptides display cytotoxic effects against cancer cells. Moreover, amino acids like tryptophan act as precursors for key neurotransmitters, influencing physiological functions. Other constituents, including phenolic compounds, xanthophylls, and proteoglycans, contribute additional antioxidant, anti-inflammatory, antihypertensive, and anticancer effects, while compounds such as N-acetylgalactosamine are essential for cellular communication. The presence of essential vitamins, including B-complex vitamins, vitamin E, and vitamin K, further supports metabolic processes, immune function, and hemostasis. Collectively, these diverse bioactive molecules underscore the significant therapeutic potential of *Cordyceps* in the development of functional foods and pharmaceutical applications.

The market value of *Cordyceps sinensis* is exceptionally high, although precise pricing can vary depending on quality and origin. Reports indicate that the fungus may fetch prices of up to USD 20,000 per kilogram (approximately INR 17 lakh), which has earned it the popular designation of "Himalayan Gold." Despite its economic importance, the commercial trade of wild *Cordyceps* is restricted in India, primarily to prevent overexploitation and illegal trafficking. Nevertheless, instances of smuggling have been reported; for example, in 2010, several Tibetan nationals were apprehended in Mechukha (West Siang district, Arunachal Pradesh) for attempting to transport the fungus across borders illegally. Certain regions, such as Dharchula, located near the Indo-Nepal border, have been identified as key transit points in the illicit trade network. From these areas, *Cordyceps* is often routed through Nepal and eventually reaches major international markets, particularly in China. Cities such as Guangzhou and Hong Kong are considered major global trading hubs for this high-value medicinal resource. China remains the largest consumer and exporter of *Cordyceps*; however, natural populations in the Qinghai–Tibetan Plateau have shown a declining trend in recent years, largely due to climate change and excessive harvesting pressure. At the global level, the *Cordyceps* market was valued at over USD 1 billion in 2022, reflecting its growing demand in pharmaceutical and nutraceutical industries. Reports from the Indo-Pacific Centre for Strategic Communications indicate a reduction in harvest levels in major producing regions such as Qinghai, further intensifying supply constraints. As a result, illegal trade from neighboring Himalayan regions, including Nepal and India, continues to supplement market demand in China. This increasing demand has also led to geopolitical concerns, with reports suggesting that personnel from the People's Liberation Army have occasionally crossed into border areas of Arunachal Pradesh in search of this valuable natural resource.

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ISSN : 2583-0910

Agri-India TODAY

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Peer reviewed
monthly newsletter

Article ID : 06/VI/21/0626

# MARINE CRYSTALS: THE ART OF PRESERVED CRUSTACEANS

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## Abstract

The global canned seafood market, valued at over $60 billion, has transformed crustaceans like shrimp, crab, and lobster into high-value, shelf-stable gourmet products. This evolution is driven by advanced thermal retort technology, which sterilizes products at 116°C to 130°C, ensuring a 2-to-5-year shelf life while maintaining "12D" microbial safety. Beyond preservation, the industry focuses on sensory integrity using nitrogen flushing and SAPP to protect natural pigments and prevent crystal formation. Modern processing now integrates a circular economy model, repurposing shell waste into profitable by-products like chitin and astaxanthin. Anchored by HACCP standards and digital traceability, the sector successfully balances industrial efficiency with the nutritional retention of Omega-3, positioning premium tinned shellfish as a sustainable, nutrient-dense staple for the health-conscious global consumer.

**Keywords:** Canning, HACCP, astaxanthin, blanching, Ready-to-Eat

## Introduction

Crustaceans like shrimp, crab, and lobster are the "high-value jewels" of the seafood industry. Canning is a vital technology that transforms these highly perishable species into shelf-stable, gourmet products, allowing for global distribution without a continuous cold chain. As of 2026, the global canned seafood market has surpassed $60 billion, fueled by a surge in "ready-to-eat" (RTE) luxury proteins and a growing "conserves" culture that treats tinned shellfish as a premium delicacy. Key trends now focus on sustainability, digital traceability, and convenience, as busy, health-conscious consumers seek out high-protein, Omega-3-rich meals that are both eco-friendly and easy to prepare.

## Types of Crustaceans Used in Canning

The canning industry utilizes a diverse array of species, with shrimp (*Penaeus vannamei* and *P. monodon*), crab, and lobster (*Homarus americanus*) forming the commercial core. For crab canning, the most significant species include the Blue Crab (*Callinectes sapidus*), the King Crab (*Paralithodes camtschaticus*), and the Snow Crab (*Chionoecetes opilio*). Emerging markets are also seeing growth in canned crayfish (*Procambarus clarkii*) and nutrient-dense krill, the latter of which is highly valued for high-tech pharmaceutical-grade oil extraction. Each species is selected based on biological traits that withstand the "retort" process; for instance, species with high astaxanthin content are preferred because their vibrant red color remains stable even under intense heat.

## Raw Material Handling and Quality Control

The journey of crustaceans into a can begins with careful raw material handling, which is essential to maintaining quality and safety. Harvesting methods whether wild capture or aquaculture affect the initial condition of the crustaceans. Stress during capture can lead to faster spoilage. Once harvested, crustaceans must be transported rapidly under chilled conditions, usually between 0 and

4°C, to slow down bacterial growth and enzymatic degradation. Upon arrival at the processing plant, raw materials undergo inspection for freshness, size uniformity, and absence of contamination. Quality control measures include grading crustaceans by size and weight to ensure consistent product batches. Sorting out damaged or substandard specimens prevents off-Flavors and textural defects in the final canned goods. Maintaining strict hygiene during these steps is critical to ensure food safety and compliance with regulations.

**Preprocessing Techniques**

Preprocessing is a critical stage that transforms raw crustaceans into a refined, "can-ready" product. This begins with rigorous cleaning to remove surface contaminants, followed by deheading, shelling, and deveining. For species like shrimp, removing the digestive tract is essential to eliminate grit and bitter off-Flavors. The most vital step is blanching, a mild heat treatment in hot water or steam. This process inactivates spoilage enzymes, reduces the initial microbial load, and firms the muscle fibres to prevent shrinkage during final canning. Precise control of time and temperature is mandatory: over blanching results in a "rubbery" texture, while under blanching fails to fix the color and leads to significant drip loss in the final tin.

**Canning Process Technology**

The canning stage is the definitive transformation of prepared crustaceans into shelf-stable gourmet products. It begins with filling, where meat is packed into tin-plated steel or aluminium cans often lined with sulphur-resistant C-enamel alongside a medium like brine, vegetable oil, or seasoned sauces to enhance flavour and heat transfer.

The most critical phase is thermal processing within an industrial retort. Here, cans are subjected to high-pressure steam at temperatures typically between 116°C and 130°C. This sterilization process is precisely calibrated to achieve commercial sterility (killing *Clostridium botulinum* spores) while preserving the delicate "snap" of the crustacean muscle. Modern innovations, such as agitated retorts and continuous processing lines, have significantly improved heating uniformity, reducing the thermal stress on the product and resulting in superior texture and color.

**Fig: 1 Canned Crustacean Products**

**Preservation and Shelf Life**

Canned crustaceans achieve long-term stability through the synergy of thermal sterilization and airtight sealing, ensuring a shelf life of 2 to 5 years. The high-heat retort process provides microbial stability by eliminating thermophilic bacteria and spores, allowing for safe room-temperature storage. Despite this stability, chemical changes like lipid oxidation and texture degradation can occur over time. To preserve quality, processors use specific additives: Sodium Acid Pyrophosphate (SAPP) is added to prevent the formation of glass-like struvite crystals, while citric acid maintains pH to stop meat discoloration. Furthermore, modern vacuum sealing or nitrogen flushing removes oxygen from the can's headspace, preventing corrosion and protecting delicate pigments (astaxanthin) from fading, ensuring the product remains vibrant and flavourful.

**Quality Assurance and Safety**

Quality assurance is anchored by HACCP and GMP frameworks, where the thermal retort stage serves as the most critical control point. This process is mathematically validated to achieve a "12D reduction," effectively eliminating *Clostridium botulinum* spores. GMPs further safeguard the product by maintaining strict hygiene during the cooling and labelling phases to prevent post-process contamination. Safety protocols also include rigorous microbiological testing for pathogens like *Salmonella* and *Listeria*, alongside specialized allergen management to prevent cross-contact. To meet global regulatory standards (Food and Drug Administration\European Food Safety Authority), processors utilize digital traceability systems. These "e-pedigrees" track the product from harvest to the final shelf, ensuring full transparency and rapid recall capabilities if needed.

**Nutritional and Sensory Aspects**

Canning effectively preserves the core nutritional value of crustaceans, maintaining high-quality proteins, heart-healthy Omega-3 fatty acids, and essential minerals like Zinc and Selenium. While high retort temperatures may slightly reduce heat-sensitive vitamins like B12, the overall mineral and caloric density remain comparable to fresh seafood. Sensory-wise, the "cooked-in-can" process enhances Savory umami notes but can result in a firmer, more fibrous texture. To maintain high consumer acceptance, processors use sensory evaluation to monitor "drained weight," color vibrancy, and flavour integrity. The goal is to achieve commercial sterility while preserving the natural sweetness and succulent mouthfeel that define premium crustacean products.

**Environmental and Economic Considerations:**

Sustainability is a key economic driver, with processors increasingly sourcing from MSC or BAP certified origins to meet global demand for ethical seafood. Adhering to strict environmental quotas and by-catch reduction protocols is now essential for market access and brand reputation. Waste management has shifted toward a circular economy, where massive amounts of shell waste are repurposed to extract high-value by-products like chitin, chitosan, and astaxanthin. These are sold to the pharmaceutical and cosmetic sectors, turning a disposal cost into a secondary revenue stream. Economically, while high energy and labor costs remain challenges, the industry is pivoting toward automated processing lines to maintain viability and capture premium price points in the international market.

**Conclusion**

The canned crustacean industry has evolved into a high-tech, value-added sector that balances advanced thermal processing with rigorous safety standards like HACCP. This ensures the delivery of nutrient-dense, shelf-stable proteins that meet the modern consumer's demand for both convenience and health. The future of the sector relies on automation and circular economy initiatives, such as repurposing shell waste to maintain economic viability. With a projected steady growth toward 2030, the industry is pivoting toward digital traceability and sustainability certifications (MSC/BAP), positioning canned crustaceans as an ethical, transparent, and premium staple in the global market.

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ISSN : 2583-0910
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Peer reviewed
monthly newsletter

Article ID : 06/VI/22/0626

# MILK FEVER IN DAIRY ANIMAL

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## Abstract

India possesses one of the largest livestock populations in the world, with about 193.46 million cattle and 109.85 million buffaloes, which play a vital role in milk production and the livelihood of rural farmers (Department of Animal Husbandry and Dairying, 2022). However, dairy animals are often affected by several metabolic diseases, among which milk fever (parturient paresis) is one of the most common and important disorders. Milk fever usually occurs around the time of calving due to a sudden decline in blood calcium levels, particularly in high-producing cows and buffaloes. The disease is mainly associated with factors such as high milk yield, improper nutrition, mineral imbalance, and advanced lactation age. Affected animals commonly show signs such as weakness, muscle tremors, difficulty in standing, and recumbency, which may lead to serious complications if timely treatment is not provided. Diagnosis of milk fever is generally based on clinical symptoms, recent history of calving, and the animal's response to calcium therapy.

**Keywords:** Metabolic Disease**,** hypocalcaemia, calving, kinked.

## Introduction

India has one of the largest livestock populations in the world, which plays an important role in the rural economy and dairy sector. According to the Basic Animal Husbandry Statistics (BAHS) of the Government of India, the country possesses a large number of dairy animals. The total cattle population in India is about 193.46 million, while the buffalo population is about 109.85 million. These animals contribute significantly to milk production and provide livelihood support to millions of farmers in the country (Department of Animal Husbandry and Dairying, 2022).

Despite having a very large population of livestock in the country, farmers often do not have adequate knowledge about the various diseases affecting animals. Due to the lack of proper awareness and veterinary information, many livestock diseases remain unrecognized or untreated at the early stage. This situation negatively affects animal health and productivity and ultimately has an adverse impact on the rural economy of India. Among the various diseases affecting dairy animals, **milk fever** is one of the most important metabolic disorder, Studies have reported that milk fever causes substantial economic losses in the dairy sector due to reduced milk yield, treatment expenses, and loss of productive animals (Goff, 2018). In severe cases, the disease may lead to the death of animals or premature culling from the herd, further increasing economic losses to farmers (Radostits *et al*., 2007). In addition, milk fever also increases the risk of other diseases such as mastitis, retained placenta, and ketosis, which further affects animal health and farm profitability (MSD Veterinary Manual, 2023).

**What is milk fever-** Milk fever is a metabolic disease of dairy animals, especially cows and buffaloes, that occurs around the time of calving due to a sudden decrease in blood calcium levels (hypocalcemia). This condition usually appears within 24–72 hours after parturition, when the demand for calcium for milk production increases rapidly and the animal's body cannot supply enough calcium. As a result, the affected animal may show symptoms such as weakness, loss of appetite, muscle tremors, difficulty in standing, and in severe cases paralysis if not treated promptly (Radostits *et al.*, 2007).

**Risk factors :** Milk fever in dairy animals is associated with several risk factors related to nutrition, management, and physiological condition of the animal. High milk producing animals are at greater risk because the demand for calcium increases rapidly at the onset of lactation. Older cows, especially those in the third lactation or later, are more susceptible as their ability to mobilize calcium from bones decreases with age. Improper feeding management during the dry period, particularly diets high in calcium before calving, can reduce the animal's ability to regulate calcium metabolism. In addition, certain breeds such as Jersey and crossbred cows, over-conditioned animals, and lack of proper mineral supplementation also increase the likelihood of milk fever around parturition.

**Pathogenesis of Milk Fever :** Milk fever develops due to a disturbance in calcium balance in dairy animals around the time of calving. At the beginning of lactation, a large quantity of calcium is suddenly required for the production of colostrum and milk. Under normal conditions, the body maintains blood calcium concentration through hormonal regulation involving parathyroid hormone (PTH) and active vitamin D, which promote the release of calcium from bones and increase its absorption from the intestine and kidneys. However, in some animals particularly high-producing or older cows these regulatory mechanisms cannot respond rapidly enough to meet the sudden increase in calcium demand. As a result, the level of calcium in the blood decreases, leading to hypocalcaemia.

The reduced calcium concentration interferes with normal neuromuscular function, because calcium is essential for proper nerve transmission and muscle contraction. Consequently, affected animals develop signs such as muscle weakness, tremors, reduced rumen activity, and inability to stand. If the calcium deficit becomes severe and treatment is delayed, the condition may progress to recumbency, circulatory collapse, coma, and even death.

**Clinical Signs of Milk Fever :** In typical cases of milk fever, affected cows initially show signs of restlessness, excitement, and slight muscle tremors, particularly in the muscles of the head and limbs. As the condition progresses, the animal becomes weak and unsteady, begins to stagger while walking, and eventually goes down into a sitting or sternal position. In many cases, the cow shows a characteristic posture in which the neck is bent or curved to one side, often referred to as an "S-shaped" or "kinked" neck. If the disease becomes more severe and treatment is not provided promptly, the animal may lie flat on its side (lateral recumbency) and may progress to circulatory failure, coma, and even death.

After the animal goes down, several additional symptoms may be observed, including a dry muzzle, dull or staring eyes, cold ears and limbs, constipation, and marked drowsiness. The heartbeat becomes weak and rapid, and the body temperature often drops below normal, especially during cold, wet, or windy weather conditions. These clinical signs mainly occur due to the significant reduction of calcium levels in the blood, which affects normal nerve and muscle function. In some cases, further complications may develop. For example, bloat (ruminal tympany) is common in animals that are unable to sit upright because the gas produced in the rumen cannot be expelled properly. Additionally, cows that remain recumbent for a long time may become susceptible to secondary problems such as pneumonia or exposure, particularly if they are left outdoors in unfavourable weather conditions.

**Diagnosis of Milk Fever :** Milk fever in dairy animals is usually identified by observing the symptoms shown by the animal, the history of recent calving, and the animal's response to calcium treatment. This disease mostly occurs within one to three days after calving, when the demand for calcium in the body suddenly increases for milk production. Farmers may notice early signs such as restlessness, loss of appetite, muscle tremors, weakness, and difficulty in standing or walking. As the condition progresses, the animal may sit in a sternal position with the neck bent to one side or may lie down and become unable to get up. Other common signs include cold ears and legs, dull eyes, reduced body temperature, and general weakness. When such symptoms appear in high-producing cows or buffaloes shortly after calving, veterinarians usually suspect milk fever.

To confirm the disease, blood tests can be carried out to check the level of calcium in the blood, which is generally found to be much lower than normal in affected animals. However, under field conditions where laboratory testing may not be easily available, veterinarians often rely on a practical method of diagnosis. In such cases, the animal is treated with intravenous calcium solution, and if the animal shows quick improvement such as becoming more alert, attempting to stand, or regaining strength it strongly indicates that the problem was milk fever. For farmers, early recognition of the symptoms and seeking timely veterinary treatment is very important because animals usually recover quickly when calcium therapy is given at the right time. Thus, careful observation of clinical signs, knowledge of the animal's calving history, and the response to calcium treatment together help in the accurate diagnosis of milk fever (Radostits *et al*., 2007).

**Treatment of Milk Fever :** Milk fever is a serious metabolic disorder in dairy animals and requires immediate treatment to restore normal calcium levels in the body. The most common and effective treatment is the administration of calcium solutions, usually calcium borogluconate, to quickly increase the level of calcium in the blood. Generally, about 300–500 ml of a 40% calcium borogluconate solution is given slowly through intravenous injection by a veterinarian. In many cases, combined mineral solutions containing calcium, magnesium, phosphorus, and dextrose are used because these minerals help improve nerve function, muscle activity, and energy levels in the affected animal.

In addition to intravenous treatment, subcutaneous injection of calcium solution at several sites under the skin may also be given, especially in field conditions. Most animals show rapid improvement within a short time after calcium therapy, often attempting to stand within a few hours. Along with medication, proper care and management are also important. The affected animal should be kept in a comfortable sitting position, placed in a clean and dry shelter, and provided with fresh water and soft feed. In cases where the animal is lying down for a long time, special attention should be given to prevent complications such as bloat or pneumonia.

After recovery, it is recommended not to milk the cow for about 24 hours, and milking should then be gradually resumed over the next few days. Early diagnosis and timely treatment greatly improve the chances of recovery and help prevent serious complications of milk fever (Radostits *et al*., 2007).

**Prevention of Milk Fever :** Milk fever can be largely prevented through proper feeding and management of dairy animals during the transition period, which usually includes the last 3–4 weeks before calving and the first few weeks after calving. During this time, special attention should be given to the animal's diet because mineral imbalance is one of the main causes of milk fever. One of the simplest preventive methods is to limit excessive green fodder and high-calcium feeds during the last two weeks of pregnancy and instead provide good quality hay or balanced dry feed. Maintaining a balanced ration with an appropriate ratio of dietary minerals such as calcium, phosphorus, and magnesium helps the animal maintain normal calcium metabolism and reduces the chances of milk fever.

Another important management practice is to keep dry cows on a relatively low-calcium diet before calving. This practice stimulates the animal's natural calcium-regulating system, enabling it to mobilize calcium from bones more efficiently when the demand suddenly increases after calving. If the body condition of the cow needs improvement before calving, energy-rich but low-calcium feeds such as cereal grains or certain types of hay can be provided. Cows that are close to calving should also be kept in an easily accessible area or paddock so that farmers can observe them regularly and detect early symptoms of milk fever.

In some cases, preventive mineral supplementation may also be useful. Calcium supplements can be given at the time of calving or shortly after calving to support the sudden increase in calcium demand for milk production. In certain situations, veterinarians may also recommend vitamin $D_3$ injections a few days before calving, which helps improve calcium absorption in the body. In herds with frequent cases of milk fever, oral calcium or mineral mixtures containing calcium and magnesium may be given around the time of calving to reduce the risk of the disease. With proper nutrition, careful observation, and timely preventive measures, the occurrence of milk fever in dairy animals can be greatly reduced.

## Summary

Milk fever, also known as parturient paresis or hypocalcemia, is a common metabolic disorder of dairy animals that usually occurs around the time of calving. The disease develops due to a sudden decline in blood calcium levels when the demand for calcium increases rapidly for milk production during early lactation. Affected animals commonly show symptoms such as weakness, muscle tremors, difficulty in standing, cold ears and limbs, and recumbency, which may lead to serious complications or even death if timely treatment is not provided. Diagnosis is generally based on clinical signs, recent history of calving, and confirmation through low blood calcium levels or rapid recovery after calcium therapy. Treatment mainly involves the administration of calcium solutions such as calcium borogluconate, along with proper supportive care. The occurrence of milk fever can be reduced through balanced feeding, adequate mineral supplementation, and proper management of animals during the transition period before and after calving, which ultimately helps improve animal health and dairy productivity.

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ISSN : 2583-0910
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Peer reviewed
monthly newsletter

Article ID : 06/VI/23/0626

# AGRICULTURE IN PURULIA DISTRICT, WEST BENGAL, INDIA

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## Abstract

The land of West Bengal varies from saline submerged land in south to hilly tracts of north West Bengal. Consequently the agro-climatic conditions varies from wet-hot to wet-cold in the north. However, Purulia is a part of Chhotanagpur Plataue, having 500mm of rainfall and hot summer of $45^0$C and above also a harsh winter cold. Because of undulating land with hillocks the conservation of rain water is difficult. Thus water-shed management is important. The prevalent cultivation system is Silviculture-Orchard-Agriculture. During winter vegetables , pulses and oilseeds can be grown with resilience irrigation.

**Keywords**: Chhotanagpur plataue, Silviculture, Orchard, Agriculture, water-shed management.

## Introduction

Purulia is a district of West Bengal from 1954. It has undulated land, average elevation being 100meters above sea level. Once this land was mostly forest area with forest dwellers. Manbazar block I & II as well as Purulia block I&II and Hura are mainly valley land. So cultivated land area is less than that of half the total area. At present with the increasing population, the forest area has been degraded to 30%. Many hillocks are without trees, however a continuous process is underway to rejuvenate through social forestry etc. The main problem of the area as reflect from people's view is scarcity of water for drinking as well as irrigations. There are rivers like Kanshabati, kumari etc. which are useful for some irrigation near the banks but due to undulating nature of land water-shed management is very much important. Because of soil erosion fertility of the land is low. Traditional varieties of crops are usually cultivated. Hence, production per unit land area is low. But with available modern technologies like drought tolerant rice varieties viz, Sahabhagi, local shati dhan, Jogesh and DRR44 are showing sustainability.

Orchards have been performing better in terms of economics with sweet orange, pomegranates, ber, guavas, mangoes etc. either as solo crop or in mixture. Initially the farmer has to take care of the plantlets sown properly with watering and other management practices for 3years. Subsequently the graphted plants will generate income and sustain it for coming 20years. In the a special short period crop Blackgram is of immense importance which provides Rhyzobium to the soil, food pulse and huge fooder for cattles during dry months. Taken all the aspects under consideration there is huge scope to manage, manipulate the productivity of crops in this area by using recent agricultural technologies in water-shed systems. Till date 40% of land area of Purulia district is monocropped. As the land is undulating, locally the land is divided into four types mainly based on elevations.

**Tarn**: Mostly top of the hillocks are known as Tarn or High lands. These are most eroded or degraded barren lands with gravels and low in organic carbon and nutrients. Planting forest trees viz. Mahua, Sal, Neem, Palas and Arjun are preferred. Earlier Eucluptus trees were planted and the growth was faster which depleted soil water rapidly. Fallen leaves decomposition, which takes more time, produces Eucluptus oil which is detrimental to soil microorganisms as well as root growth of indigenous plant spices.

**Baid**: Below Tarn the land areas which are usually flat or with little slope is also eroded and mostly dried. Low in nutrient content laterite soil needs application of organic matter and liming and watershed management to collect runoff water from Tarn and Baid during rainy season to be used for next 3-4 months. Orchard plantation is generally recommended in the area or cultivation of black gram which is one of the important crops of the region. Blackgram can also be grown in the spaces of early stage of orchard plantation for first3-4 years. It will increase fertility and microbial population to increase biological nitrogen fixation as well as conserve the soil water by covering the land. However, rainy and winter season vegetables can be grown in between spaces. From 5years onwards spices like ginger and termaric are usually grown successfully under shade micoclimatic conditions. Sometimes rice of 60 (after transplanting) viz. Shatia, Lalat etc. are also grown.

**Kanali**: These are the land areas where cultivation can be taken up easily. Midium duration rice varieties are mainly grown or summer-rainy season vegetables are grown profitably. The vegetables grown in these areas are bittergourd, bottle gourd, pumkin, pointed gourd,ridge gourd etc. These areas are mainly double cropped. Sometimes rice-wheat sequence is followed. Wheat can be grown in these areas in January sowing and harvested in April, if some irrigation source is there, wheat usually requires much less water. In winter, toria sorsan, Bengal gram, pea, onion, garlic, carrot, radish, cabbage, cauliflower, broccoli, and specially tomatoes are grown. The reason is that in kanali land situation the land is with more organic carbon, nutrient content is medium and less acidic also the soil can retain moisture for longer period so that the crops are fertilizer responsive. Intesive agriculture in these areas may thus boost the food production vis-a –vis agricultural marketing of the daily needs and the income of the farmers. Sometimes, long duration Kavur varieties of elephant foot arum is also cultivated.

Rohin is observed in these areas on first of Bengali month Ashara and after ploughing often rice cultivation started by broadcasting the dry seeds. Only if sufficient rainfall is their for few succecive days then rice seeds germinated but because of erratic rainfall DSR method of rice cultivation failed causing increased seed costing in cultivation.

**Bahal (Low land)**: These are the low laying areas with some stagnant water mainly collected from runoff water during rainy season. Usually about 150 days rice varieties are grown. Productivity is good when integrated pest management (organic or synthetic) protections are taken. Manbazar block I & II and some areas of Purulia I&II and Raghunathpur, valley areas of Jhaldah and Kashipur-Hura are under this rice cultivation. Sirkabad area of Arsha block is mostly under sugar cane cultivation. As sugar cane is a long duration crop hence water requirement is high and grown traditionally at the foot hillock (semicircle) valley area with disease resistance modern sugar cane varieties. Medium to high production are recorded after harvest. These are mainly monocropped area (bahal) and after rice harvesting and a subsequent fallow to reduce moisture Toria sarson or redgram are grown. It is noted that in rice cultivation of the situation farmers sometimes organic fertilizer as N source like mustard oil cake after transplanting, but this is harmful to the growth ,specially root growth, because anaerobic decomposition under submerged situation takes about 3 weeks and emission gases like nitrogen oxides, sulphur oxides and hydrates causes reduction of root growths. Thus mustard oil cake should be applied at the time of ploughing the land mostly in dry condition and subsequently rain water wet the soil. After 2-3 ploughings and land leveling transplanting of seedlings are arranged so that ammonium nitrogen is available at the time of tillering, so that gas emission is minimized.

Apart from all these Balarampur, Baghmundi, Jhaldah, Bandwan and Barabazar though situated in high land have some water sources and vegetables cultivations are carried out by farmers at their high skill with good management, production and profitability. In some areas, tomatoes, cucumber and Dolicus there is a scope for sustainable rapid growth.

**Conclusion**

It is evident that inspite drought prone area a successful silvi-Horti-agricultural system under water-shed management with new agricultural technologies can be adopted to convert it from monocropped to multiplecropped areas for optimizing productivity and income. In the way Govt. and Govt. agencies may cooperate with small modern tools and FPOs should be encouraged providing seeds and marketing the produces. As Purulia is to some extend backward hence with these activities a rapid development may be achieved soon.

ISSN : 2583-0910
Agri-India TODAY
visit us at www.agriindiatoday.in

Peer reviewed
monthly newsletter

Article ID : 06/VI/24/0626

# OYSTER MUSHROOM CULTIVATION

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## Introduction and Worldwide Scenario of Oyster Mushroom

*Pleurotus ostreatus* also referred to as the Oyster Mushrooms are a category of edible mushrooms that belong to the class Agaricomycetes and are widely spread to various climatic conditions. They naturally occur on dead woods and organic substances particularly in the forest ecosystems. The Oyster Mushrooms are also known to have a shell or fan shaped tops, soft texture and have a mild aroma which is slightly sweet; a characteristic that renders them very appreciable in food preparation. They are nutritionally abundant in proteins, dietary fiber, and vitamins (primarily, belonging to the B-complex) and low in fat, which makes them a perfect ingredient of a healthy diet. They have become very important in sustainable agriculture because of their effective capacity to transform agricultural residues into nutritious food.

The cultivation of Oyster Mushroom is traced in 1917 when Flank reported it in Germany. It is commonly known as one of the richest-proliferated edible mushrooms in the world with it being used in the third position globally next to genus Agaricus and Lentinula. China is the producer of almost all oyster mushroom in the world with nearly 85 percent of the total output of oyster mushroom and the annual production volumes are almost one million tonnes. Other significant producers are Japan, South Korea and Thailand where oyster mushrooms are significant in culinary practices and medicinally. Oyster mushroom cultivation is increasingly getting popularity in India because low cost of production, less labour force and high yield potential in addition to its ability to be cultivated throughout the year.

## Importance and Scope of Oyster Mushroom

Oyster Mushrooms are popular edible mushrooms because they have two purposes, nutrition and health promotion. They contain the necessary minerals, which are useful to the human organism, and contain significant vitamins like Vitamin C and Vitamin B complex, with high amounts of niacin. Oyster mushrooms have been known in traditional Chinese medicine to benefit both the innate and adaptive systems. Oyster mushrooms are also gaining acknowledgment when it comes to sustainable farming because it has been seen to effectively transform farm waste into highly nutritional food. This change is not only ensuring reduction of environmental contamination, but it also enables an establishment of a cyclic system of agriculture. Oyster mushrooms are high in protein, fiber and key minerals and will easily help in the growing global trend of consuming plant based and environmentally friendly eating trends. Oyster Mushrooms are also very important in the natural ecosystem, as they are the main decomposers in the ecosystem and in the woody materials, such as lignin and cellulose, which are complex compounds, therefore, they help in recycling of nutrients and making the soil fertile. They are especially relevant in the sustainability of waste management because of their high efficacy in colonising a large variety of substrates.

One of the good opportunities available to growers would be oyster mushrooms since it is one of the agricultural practices that can be grown with minimum investment and yet produce high returns. Fresh and dried mushrooms both have a big demand and usually command high prices in both local and foreign markets. Farmers also have an opportunity to get more income by processing mushrooms into value added produce such as powders and pickles. Also, the remaining used substrate of growth is a good organic fertilizer that offers an additional source of income and promotes the culture of farming sustainably.

**Classification and Species of Oyster Mushroom**

From a taxonomic perspective, oyster mushrooms can be classified as following:

- **Kingdom:** Fungi
- **Phylum:** Basidiomycota
- **Class:** Agaricomycetes
- **Order:** Agaricales
- **Family:** Pleurotaceae
- **Genus:** *Pleurotus*
- **Species:** *ostreatus*

*Pleurotus genus* has more than 40 species that have been identified across the world and in the recent years, close to 25 species in the genus have been successfully produced in different regions globally. A few of these species are especially significant because of their high level of cultivation and economic significance. Oyster mushrooms that are commonly grown are:

- ***Pleurotus ostreatus* (Grey Oyster Mushroom)**
  This species grows best in cooler climates and is one of the most popular varieties.
- ***Pleurotus sajor-caju***
  It performs well in warm conditions, making it suitable for cultivation throughout the year.
- ***Pleurotus florida* (White Oyster Mushroom)**
  Recognized for its bright white caps, rapid growth, and preference for warm, humid environments.
- **Other important commercially grown species:**
  - *Pleurotus eryngii* (King Oyster Mushroom)
  - *Pleurotus citrinopileatus* (Golden Oyster Mushroom)
  - *Pleurotus djamor var. rosae* (Pink Oyster Mushroom)

| Variety | Colour | Temperature Range | Special Feature |
|---|---|---|---|
| *Pleurotus ostreatus* | Grey/white | 20–30°C | Most Common |
| *Pleurotus ostreatus* | White | 18-28°C | High yield |
| *Pleurotus sajor-caju* | Cream | 20-32°C | Heat tolerant |
| *Pleurotus djamor* | Pink | 22–30°C | Fast growing |
| *Pleurotus citrinopileatus* | Yellow | 18-25°C | Attractive color |

**Morphology and Lifecycle of Oyster Mushroom**

The fruiting bodies of the Oyster Mushrooms are unique and resemble shells or spatulas. They may come in various colors based on the species; they may be white, cream, grey, yellow, pink, light brown or even blue. Their smell is also pleasant and slightly sweet and is mostly likened to anise or licorice.

| S. No. | Morphological Characteristics | Description |
|---|---|---|
| 1. | Cap shape | Shell- or fan-shaped, convex to flat |
| 2. | Gills attachment | Decurrent (extend down the stem) |

| S. No. | Morphological Characteristics | Description |
|---|---|---|
| 3. | Stem | Short, lateral, off-center |
| 4. | Cap size | 5–25 cm diameter |
| 5. | Cap colour | White, grey, tan; sometimes blue, pink, yellow |
| 6. | Gills colour | White, turning cream or pale yellow |
| 7. | Cap surface | Smooth, velvety; slightly sticky in moisture |
| 8. | Gills arrangement | Closely spaced |
| 9. | Stem size | 2–10 cm long, 1–5 cm thick |
| 10. | Stem colour | Whitish to pale grey, may develop spots |
| 11. | Stem surface | Smooth, slightly fibrous |
| 12. | Flesh texture | Thick, firm, juicy |
| 13. | Flesh colour | White to creamy |
| 14. | Odor | Mild, slightly sweet (anise-like) |
| 15. | Spore print | White to pale yellow |
| 16. | Spore shape | Elliptical to cylindrical |
| 17. | Spore size | Elliptical to cylindrical |
| 18. | Spore surface | Smooth |

Oyster mushrooms have the characteristic life cycle of basidiomycetes that includes the germination of the haploid basidiospores into monokaryotic, independent growing mycelium. Upon meeting two complementary monokaryotic hyphae, they plasticly merge to create a dikaryotic mycelium (n+n), which is plastically connected by clamp and has two genetically different nucleus in each cell. This dikaryotic mycelium under appropriate environmental conditions like proper temperature, humidity and light will progress to fruiting bodies which will contain basidia and finally, the nuclear fusion (karyogamy) and protein synthesis (meiosis) will take place to develop new basidiospores, thereby finalizing the life cycle.

Some species are also allowed to develop asexual structures in addition to sexual reproduction like synnemata. The mating system of the oyster mushrooms is a bifactorial heterothallic system that is regulated by two mating-type factors that determine compatibility among the strains. Their high germination rate of spores, easy to grow, and also adaptable to laboratory conditions makes them very appropriate in breeding programs. Improvement of strains has been further promoted by modern methods, like molecular genetics and recombinant DNA technology, with interests in improvement of selected characteristics of strains like temperature toleration, contaminant resistance, low sporulation and nutritional and enzymatic properties.

**Climatic Requirements for Cultivation**

The growth and productivity of Oyster Mushroom are affected by climatic requirements, mainly temperature, humidity, and ventilation. Oyster Mushrooms are known for their adaptability, but every species grows best under specific climatic requirements.

The temperature is the most important climatic factor for the growth and productivity of Oyster Mushrooms. The most commonly grown species, i.e., Pleurotus ostreatus, grows best at temperatures ranging from 20°C to 30°C during spawn run, whereas fruiting requires cooler temperatures, i.e., from 15°C to 25°C. Too high temperatures may completely stop the growth, whereas low temperatures may cause delayed growth.

The humidity is another important climatic factor for the growth and productivity of Oyster Mushrooms. Relative humidity should be maintained at 80-90% to ensure proper fruiting and to prevent drying of pinheads. Too low humidity may cause deformed Oyster Mushrooms, whereas too much humidity may cause contamination.

Ventilation and light are another important climatic factor for the growth and productivity of Oyster Mushrooms. Oyster Mushrooms need proper ventilation to remove $CO_2$, as Oyster Mushrooms produce $CO_2$ during respiration. Too much $CO_2$ may cause elongated stems and poor cap formation.

**Infrastructure and Growing House**

Simple low-cost setup in a controlled environment required for oyster mushroom cultivation. This depends on scale, investment capability, and climatic conditions.

Traditional cultivation practices use thatched huts, bamboo works, or temporary sheds. But today, a semi-controlled or controlled growing house is recommended. A well-designed growing house helps in better insulation, ventilation, and humidity control. This improves yield and reduces the risk of contamination. A good growing house should have a controlled temperature and humidity level, protect against pests, and provide adequate ventilation. It should have separate sections for substrate preparation, spawning, incubation, and cropping. This helps in segregating the sections, which reduces cross-contamination and improves efficiency. Polythene sheets, racks, and foggers may be used to support controlled cultivation. In commercial cultivation, polyhouses and environmentally controlled chambers are recommended. This helps in cultivation throughout the year regardless of weather conditions.

Growing house

**Equipment and Materials Required**

Essential tools and materials needs for efficient mushroom cultivation and to ensure proper handling and hygiene. Basic equipment includes knives or choppers for substrate cutting, drums or tanks for boiling or pasteurization, thermometers and hygrometers for monitoring environmental conditions, and sprayers for maintaining humidity. Sterilization and pasteurization equipment are critical to eliminate competing microorganisms and improve spawn colonization. In small-scale setup, hot water treatment is commonly used, whereas larger farms may utilize steam sterilization. Other important materials include high-quality spawn, polythene bags, racks for stacking, and disinfectants for maintaining hygiene.

Clean and properly maintained equipment has been identified as a key factor in reducing contamination and increasing biological efficiency. Therefore, maintaining sanitation throughout the process is as important as the cultivation itself.

**Selection of Suitable Site**

The necessary equipment required for efficient cultivation of mushrooms. This ensures efficient handling of materials. The necessary equipment required includes knives or choppers for cutting the substrate, drums or tanks for boiling or pasteurization, thermometers, hygrometers, and sprayers.

Sterilizers or pasteurizers are required. This helps in eliminating competing organisms. Hot water treatment is commonly used in small-scale cultivation, but in large-scale cultivation, steam sterilizers are used. Other necessary materials required are spawn materials, polythene bags, racks, and disinfectants. It has been established that one of the key factors in maintaining efficiency in mushroom cultivation is the use of clean equipment. This emphasizes the need to maintain sanitation in the cultivation process.

**Types of Substrates Used**

One of the major advantages of oyster mushroom cultivation is that it can be grown on a wide variety of different substrates that are usually agricultural wastes. The substrate plays an important role in the yield and growth rate of the oyster mushrooms. The substrates that can be used for the cultivation of oyster mushrooms include wheat straw, paddy straw, maize cobs, sugarcane bagasse, sawdust, and many more. Among the substrates that can be used for the cultivation of oyster mushrooms, paddy straw and wheat straw have been found to be the most efficient substrates for the cultivation of oyster mushrooms due to the favourable content of cellulose and lignin. Pre-treatment of the substrate is an essential factor for the cultivation of oyster mushrooms. Good preparation of the substrate for spawn running also increases yields and reduces contamination. Supplementation with nutrients such as bran may also improve production, but it requires careful management to avoid contamination. The ability to utilize agricultural wastes not only reduces the cost of production but also promotes environmental sustainability**.**

**Collection and storage of substrate**

The substrates for mushroom serve as the major source of nutrients and contain carbon (45-55%), nitrogen (0.5-2%), and minerals necessary for the development of the mushroom. The efficiency of mushroom development largely depends on the quality of the substrate at the time of use. Inadequate storage of substrates can lead to a reduction of biological efficiency by 15-30%. Lignocellulosic substrates such as straw contain cellulose, hemicellulose, and lignin necessary for the development of the mushroom.

The time and method for collecting the substrates are also significant. The substrates, such as cereal straw, must be collected during the right stage of maturity to ensure the ideal C:N ratio, i.e., 60:1 to 80:1, for the growth of mushrooms. The substrates must be dried to reduce the moisture level to below 12% for storage, as high moisture content above 20% will lead to rapid growth of microorganisms in 2-3 days. Contamination in the field also contributes to the level of microorganisms, affecting the next step in the process, i.e., pasteurization. The substrates must be dried properly before storage. The drying process reduces the moisture content to 8-12%, thus inhibiting the growth of bacteria and molds. The substrates can be dried in the sun, or mechanical drying can be done for faster results. The substrates must be cut into smaller sizes, i.e., 2-5 cm, for efficient storage. In some cases, heat treatment also reduces the microorganisms.

Dry lignocellulosic substrates have a longer storage period of 6-12 months when stored under appropriate conditions. The conditions for storing lignocellulosic substrates include a temperature range of 15-25°C and a relative humidity of less than 60%. Excessive relative humidity above 70% causes an increase in the moisture content of the substrate, resulting in mold formation such as Aspergillus and Penicillium. During longer storage periods, a small amount of nutrient loss may also occur. When the substrate is hydrated or treated, it becomes less stable because of the higher moisture content of 60-70%. Such substrates have a short storage period of 24-48 hours. Refrigeration of hydrated substrates extends the period of storage for 5-7 days; however, the chances of contamination are also higher. Bags of sterilized substrates are stored for a period of 30-60 days at a controlled temperature of 13-21°C and a relative humidity of 50-60%. During longer storage periods, the chances of substrate contamination are higher. Grain substrates have a higher nutrient content and are more prone to contamination; therefore, they are stored in airtight containers at a temperature of 15-20°C for a period of 30-45 days.

### Types of spawn

Spawn is a material containing actively growing mycelium used for inoculation of the substrate for mushroom cultivation. The type of spawn used influences the rate of growth and the amount of yield as well as the risk of contamination. Spawn is classified into different types depending on the material used as a carrier.

**1. Grain Spawn:** Grain spawn is the most commonly used due to its high nutrient values and rapid growth rates. It offers numerous inoculation sites; therefore, rapid colonization is achieved (10-12 days). It is highly susceptible to contamination and demands proper sterilization.

**2. Sawdust Spawn:** Sawdust spawn is used for woody substrates and ensures stable and uniform growth rates. It has low nutrient values compared to grain spawn; therefore, contamination is low. It also offers stable colonization rates.

**3. Plug Spawn:** Plug spawn is prepared using wooden dowels and is used for log cultivation. It ensures deep penetration into the wood and minimizes contamination risks. It demands a longer period for complete colonization (8-16 weeks).

**4. Liquid Spawn:** Liquid spawn is a newly developed method of spawn production, wherein the mycelium is cultivated in liquid form. It ensures rapid multiplication and uniform distribution of the spores. It is highly effective but demands strict sterile conditions and proper handling.

### Substrate preparation techniques

Preparation of substrate is an essential step in the cultivation of oyster mushrooms. It transforms the substrates into a form suitable for the development of the mycelium. It is done through the selection of substrates, conditioning of substrates, pasteurization of substrates, and spawning of substrates.

In the first step of substrate preparation, substrates such as paddy straw, wheat straw, sawdust, and other agricultural wastes are selected for the cultivation of oyster mushrooms. These substrates contain cellulose and hemicellulose, which are beneficial for the development of the mushroom. The substrates are then chopped into small pieces of 2-5 cm to make the best use of space. The chopped substrates are then soaked in clean water for 8-16 hours to maintain uniform moisture content of 60-70%. It is extremely important to maintain the moisture content of the substrates; otherwise, the development of the mushroom will be adversely affected. After the substrates are properly soaked in water, pasteurization of the substrates is done to remove harmful microorganisms from the substrates. Pasteurization is done by hot water at 65-80°C for 1-2 hours or through steam at controlled temperatures.

Finally, the prepared substrate is mixed with the mushroom spawn in the ratio of 2-5% for the uniform colonization of the fungi. This mixture is then filled in perforated plastic bags or containers to allow for a limited exchange of air. Proper compaction is maintained to allow for the retention of moisture and aeration. These prepared bags of substrates are maintained in the required conditions of incubation, i.e., 20-25°C. In this phase, the fungi colonize the entire substrate, and the process of substrate preparation is complete.

**Methods of pasteurization (hot water, steam, chemical)**

Methods of pasteurization in the cultivation of oyster mushrooms include the following, all intended to control competing microorganisms while maintaining the beneficial microbalance and quality of the substrate.

Hot water pasteurization entails immersing the cut substrate in hot water maintained at temperatures ranging from 65 to 80 degrees Celsius for 1 to 2 hours. The range of temperatures ensures the destruction of all harmful microorganisms without affecting the lignocellulosic structure. The substrate is then drained to obtain the desirable 60 to 70 percent moisture content for spawning. The method is easy to carry out, especially for small-scale cultivation, but some nutrient loss occurs due to leaching.

Steam pasteurization is a more controlled method whereby the substrate is exposed to steam at a temperature of 60-70°C for a period of 4-6 hours. This method provides uniform heat penetration and nutrient retention compared to hot water treatment. This method is widely applied in large-scale operations since it gives reliable results and prevents any chances of contamination.

Chemical pasteurization involves the use of chemicals such as lime or calcium hydroxide and other disinfectants to inhibit the growth of microorganisms. In the lime method of chemical pasteurization, the substrate is soaked in alkaline water with a pH of above 11 for a few hours and then drained. This method is simple and does not require any heat for the process; however, the substrate has to be handled carefully since it may contain chemical residues that inhibit the growth of mycelium.

All these methods are based on the concept of developing a favorable environment for the growth of oyster mushroom mycelium; however, the success of these techniques also depends on the conditions of temperature, time, and moisture

**Moisture Management in Oyster Mushroom Substrate**

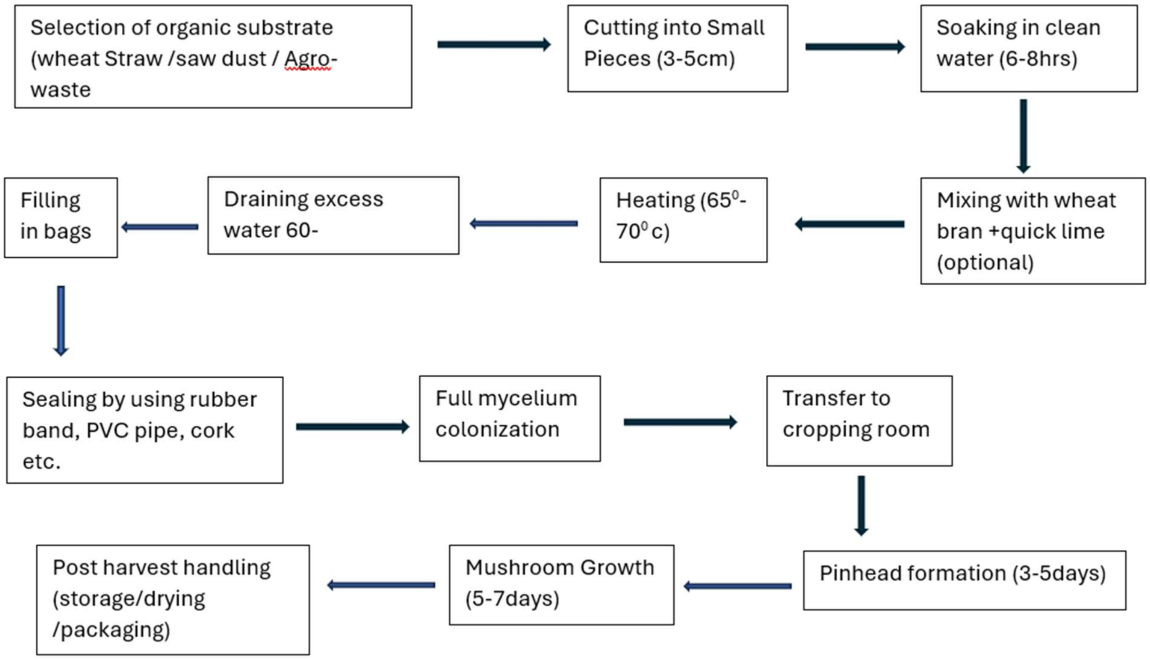
One of the most important factors for the successful cultivation of oyster mushrooms is moisture management. Oyster mushrooms are classified as saprophytic mushrooms and require water for nutrient absorption, enzyme production, and growth. Water helps to transport nutrients, facilitates metabolic activities, and maintains a healthy level of gas exchange in the substrate. Thus, it is important to maintain an optimum level of moisture for fast growth, low level of contaminants, and high yield.

The level of moisture content has a significant impact on the physical and biological characteristics of the substrate used for mushroom cultivation. Fungal hyphae require a sufficient level of water for nutrient transport and metabolism. Deficiency of moisture results in a low level of enzyme production and slows down the growth of the mushroom. On the contrary, a high level of moisture reduces the level of oxygen available for the growth of the mushroom since it becomes anaerobic. In oyster mushroom cultivation, the optimum level of substrate moisture is 60-70%. This level of moisture is sufficient for the growth of mushrooms while inhibiting the growth of harmful microorganisms. The substrate's moisture level must be adjusted before spawning. For example, materials like wheat straw and paddy straw must be soaked in water for 8 to 16 hours to ensure proper absorption. After soaking, the substrates must be drained of excess water to ensure that the desired level of moisture is achieved. Substrates with less than 55% moisture have slow colonization, while substrates with more than 75% moisture tend to compact and have low levels of aeration, thus increasing the risk of contamination. One of the easiest ways of checking the moisture level of the substrate is by doing the squeeze test. The squeeze test only allows a few drops of water to come out of the substrate. In the spawn run process, the moisture level of the substrate tends to vary. The substrate also loses moisture due to evaporation. The heat generated by the respiration of the mycelium also causes the substrate's temperature to rise. This results in the substrate's moisture level falling. To counteract this effect, the relative humidity must be maintained at 70 to 80%. Low levels of moisture will lead to uneven growth. Excessive levels of moisture will lead to low levels of oxygen.

The moisture levels also affect the enzymes in the case of the oyster mushrooms. The enzymes, such as cellulase and ligninases, perform optimally in higher moisture levels. This is helpful in the degradation of the substrates. However, high moisture levels might inhibit the availability of oxygen and the production of enzymes. A balance of moisture and aeration is required for the optimal use of the substrates and the development of the mushrooms.

**Organic oyster mushroom cultivation**

Organic Oyster Mushrooms cultivation is done in an eco-friendly manner. The process begins with substrate preparation and ends with post-harvest handling. In the first step, organic matter like wheat straw, sawdust, wood shavings, etc., which can be locally found in nature, is cut into small pieces and soaked in clean water. In some cases, a little quicklime is added to maintain pH levels. In the next step, pasteurization is done by pouring hot water or using hot water spray to eliminate contaminants. The substrate is then filled in polypropylene or eco-friendly bags. Fresh mushroom spawn is then filled in layers in a clean environment. The bags are then tightly sealed with rubber bands, PVC pipes, or foam corks to allow for aeration. These bags are then kept in a dark room maintained at 25 to 30°C for 2 to 3 weeks to allow for full colonization. Later, these bags are shifted to a cropping room with good ventilation, indirect lighting, and 80 to 90 % humidity. Watering is done regularly to keep moisture levels up. Small pinheads appear within a few days, and they develop into mature mushrooms, which are harvested by gently twisting near the base within 3 to 4 days of fruiting.



Flow diagram of organic oyster mushroom cultivation

Bags of oyster mushroom

## Integrated Oyster Mushroom Farming

Integrated oyster mushroom farming is a sustainable agricultural practice that combines mushroom cultivation with other farming activities to improve resource efficiency and minimize waste. The process begins with selecting a carbon-rich substrate—commonly agricultural byproducts such as rice straw, wheat straw, or used coffee grounds. This substrate is pasteurized, usually through hot water or steam treatment, to eliminate competing microbes, then inoculated with oyster mushroom spawn. Once inoculated, the substrate-filled bags are transferred to a fruiting room, where exposure to light and fresh air stimulates mushroom development.

The term "integrated" refers to the reuse of spent mushroom substrate, which remains rich in nitrogen, as nutrient-dense compost or livestock feed. This byproduct serves as an effective organic fertilizer, closing the loop and enhancing the system's sustainability. In such setups, environmental conditions favourable for oyster mushrooms—high humidity and mild temperatures—are maintained naturally. Placing the mushroom unit near water sources or within greenhouses allows plant transpiration to supply moisture, while the mushrooms' carbon dioxide emissions support photosynthesis in nearby plants. These plants, in turn, provide shade that helps keep the growing area cool.

This synergistic arrangement reduces the need for costly climate control systems, making it especially beneficial for small-scale farmers. Additionally, by alternating mushroom cultivation with seasonal crops, farmers can secure year-round income, produce nutritious food for their households, and improve soil fertility using mushroom-derived compost.

## Recent advances in Oyster Mushroom Cultivation

Recent advances in oyster mushroom (Pleurotus spp.) cultivation reflect a shift from traditional practices to more scientifically driven approaches, particularly in substrate formulation and environmental management. Studies highlight that the composition of the growth medium plays a crucial role in mycelial development, fruiting, and overall biological efficiency. Substrates rich in lignocellulosic materials—especially wheat straw—have proven highly effective due to their favourable structure for air circulation and nutrient availability, supporting rapid mycelial growth. Among these, wheat straw stands out as the most suitable base material. A key advancement has been the refinement of spawning rates. Research indicates that a 6% spawn inoculation level works well under subtropical conditions, while increasing the rate to 8% can speed up colonization and shorten the time to primordial formation in Pleurotus pulmonarius. This acceleration supports earlier harvests and improved yields, especially when combined with strategic nutritional supplementation. Enhancing substrate nutrition has also become a focal point. Agro-industrial byproducts containing nitrogen, such as soybean and chickpea straw, have been shown to significantly boost yield and biological efficiency. Nitrogen is essential for fungal protein synthesis and enzyme function. Adding cottonseed meal to wheat straw, for instance, has resulted in a biological efficiency of up to 77.65%, underscoring the importance of balancing carbon-rich materials with nitrogen sources for optimal growth.

Beyond substrate improvements, environmental control has emerged as a critical factor. Light quality, in particular, influences both yield and mushroom morphology. Findings suggest that blue and red-blue light spectra enhance productivity and cap size more effectively than red light or darkness, indicating light's role not only in triggering fruiting but also in supporting development. Together, these innovations—optimized substrates, precise spawning rates, targeted nutrient enrichment, and controlled lighting—represent a move toward precision farming in oyster mushroom production. They enable higher yields, better efficiency, and improved quality, while promoting sustainable agriculture through the reuse of agricultural waste. As research progresses, these methods are likely to further transform the cultivation landscape.

## Future Prospects

The future of oyster mushroom cultivation is highly promising, with several emerging opportunities: Sensors enable real-time adjustments, allowing farming systems to respond dynamically. Automated controls modify growing conditions based on continuous data streams, ensuring immediate reactions to changes in temperature. Humidity remains stable thanks to rapid feedback mechanisms, while carbon dioxide levels are monitored constantly. Lighting is fine-tuned according to the specific needs of plants at each growth phase. Artificial intelligence aids decision-making by identifying patterns in data, and consistent oversight from digital systems leads to more uniform results. Precision in managing variables contributes directly to improved output.

Agricultural byproducts, customized by region, are being repurposed into new growing media when combined with enriched supplements. Yields increase where locally sourced waste is integrated with targeted nutritional enhancements in soil formulations. In biotechnology, one emerging focus is engineering strains of Pleurotus fungi for greater efficiency. These modified varieties may show stronger resistance to disease than existing types. Some research seeks to enhance their health-promoting properties through genetic modifications, while other efforts aim to increase productivity without compromising quality. Advances in this area could transform current cultivation practices. Scientists are also working to elevate nutrient content using precise genetic techniques.

New product developments featuring oyster mushrooms—rich in protein, fiber, and bioactive compounds—are opening fresh market possibilities. Given these qualities, researchers envision their use in functional foods, plant-based meat alternatives, or specialized dietary products in the future. At scale, used mushroom substrate can be reused in composting or as animal feed, strengthening agricultural resilience. Its integration into circular systems reduces waste and improves soil quality. When processed into biofertilizers or protective plant coatings, the material serves purposes beyond disposal, adding economic and ecological value. These applications help create a more self-sustaining farming model that depends less on outside resources. In response to changing climate conditions, new crop varieties are being developed to succeed in varied environments. These approaches aim to sustain harvests year-round, especially in regions experiencing prolonged warmth. By adapting methods to local conditions, farming can persist despite uncertain weather. Resilience grows when crops evolve alongside shifting environmental patterns, and stable yields become more achievable when adaptability is embedded in cultivation practices. Cultivating oyster mushrooms presents growing opportunities—simple methods align with increasing consumer demand. Low startup costs make it accessible for small entrepreneurs, bringing income to rural areas with limited employment. The potential lies not only in profitability but in the ease of entry. Rising demand favors agile, small-scale producers who can respond quickly to market shifts. Today, oyster mushroom farming combines innovation with practicality, offering an environmentally sound business option. As research progresses and techniques spread, this sector may enhance food security, promote sustainable practices, and stimulate local economies—an evolution unfolding steadily and quietly.

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ISSN : 2583-0910
Agri-India TODAY
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Peer reviewed
monthly newsletter

Article ID : 06/VI/25/0626

# FROM SACRED TO STRESSED: ECOLOGY OF INDIA’S CULTURAL RIVERS

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## Where faith meets freshwater

Across India, rivers are more than channels of water. They are mothers, goddesses, and lifelines woven into ritual, memory, and livelihood. The Ganga, Yamuna, Narmada, Godavari, Kaveri, and countless others shape settlement patterns, festivals, agriculture, and fisheries. People come to their banks for prayer, purification, cremation rites, and celebration.

Yet, beneath this reverence, many cultural rivers are under growing ecological stress. The paradox is stark: the most sacred rivers are often the most burdened.

## A river is a living system, not a pipeline

Ecologically, a healthy river depends on three fundamentals:

1. **Flow** that keeps water moving, oxygenated, and self-cleansing
2. **Sediment** that builds habitats and spawning grounds
3. **Biodiversity** that stabilizes food webs from plankton to fish

When these are disrupted by dams, barrages, sand mining, sewage inflow, and excessive abstraction, the river’s character changes. The water may still be present, but the *ecology* that makes it a river begins to fade.

## Rituals, waste, and unintended consequences

Cultural practices often bring large gatherings to riverbanks:

- Mass bathing during festivals
- Idol immersion with paints, plaster, and decorations
- Offerings wrapped in plastic and cloth
- Cremation residues and ritual materials

Individually meaningful acts accumulate into ecological loads—nutrients, metals, plastics, and organic matter. During lean flow periods, these inputs concentrate, leading to algal blooms, foul odours, and oxygen stress.

The river absorbs devotion, but it also absorbs waste.

### Barrages: still water in a flowing tradition

Many sacred cities are upstream of barrages where water slows and stagnates. Reduced velocity increases residence time, allowing nutrients to accumulate and phytoplankton to multiply. Water turns green, cyanobacteria dominate, and dissolved oxygen fluctuates sharply between day and night (Kumar et al., 2025).

To pilgrims, the river appears calm and full. To an ecologist, it behaves like a pond.

### Sediment, sand, and spawning grounds

Sand mining to support construction removes the very substrate fish use for breeding. At the same time, dams trap sediment upstream, starving downstream stretches. The result is habitat loss on both sides—burial of rocky beds upstream and channel erosion downstream.

Fish that once spawned in clean gravel and sand lose their nurseries.

### What fishers notice before scientists do

Fisher communities often speak of:

- “Green water” that clogs nets
- Declining catches near towns
- Disappearance of current-loving native fishes
- Foul smell during low-flow months

These observations mirror ecological indicators: plankton blooms, oxygen depletion, and habitat simplification. Traditional knowledge frequently detects river stress earlier than formal monitoring.

### The invisible signal: plankton

Microscopic algae respond within days to changes in nutrient levels and flow rates. Pollution-tolerant genera become dominant where organic load and stagnation coincide (Pal et al., 2024). Tools like Palmer’s Pollution Index can quickly detect this shift, revealing ecological stress long before fish kills occur.

In cultural rivers, the earliest warning signs are often microscopic.

### When sacred water becomes unsafe water

Ecological stress has public health implications:

- Cyanobacterial blooms can produce toxins
- Low oxygen promotes foul-smelling anaerobic conditions
- Pathogens persist longer in slow-moving water

Thus, river degradation is not only an ecological issue but also a human one, affecting millions who rely on these waters for daily use.

### Restoring respect through restoration

Protecting cultural rivers does not mean abandoning traditions. It means adapting practices with ecological sensitivity:

- Eco-friendly materials for idol immersion

- Proper collection of ritual waste
- Ensuring environmental flows across barrages
- Regulating sand mining
- Treating sewage before discharge

Faith and ecology need not be in conflict; they can reinforce each other.

### A new form of reverence

For generations, people have worshipped rivers through ritual. The next step is to worship them through restoration—by keeping them flowing, clean, and biodiverse.

A sacred river is not defined by mythology alone, but by the health of its water, its fish, and its invisible plankton. When we protect these, we protect both ecology and culture.

### Conclusion

India’s cultural rivers carry stories, prayers, and livelihoods. They deserve to carry life as well. Recognizing the ecological stress beneath the sacred surface is the first step toward meaningful conservation. Reverence must now be expressed not only in rituals on the banks, but in actions that allow the river to remain a river.

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ISSN : 2583-0910
Agri-India TODAY
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Peer reviewed
monthly newsletter

Article ID : 06/VI/26/0626

# PODO FARMING SYSTEM: AN INDIGENOUS NATURAL FARMING PRACTICE OF BASTAR, CHHATTISGARH, INDIA

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## Introduction

The Bastar region of Chhattisgarh, India, dominated by dense forests, is home to tribal communities for whom agriculture is deeply intertwined with culture, tradition, and spirituality. Farming here is not merely an economic activity but a way of life rooted in ecological harmony. One such traditional system is the Podo farming system, a localized form of shifting cultivation practiced for generations.

Before initiating cultivation, communities perform rituals to seek permission from nature, particularly the Earth Goddess (Bhumagadi), reflecting their reverence for natural resources. Agricultural activities, from sowing to harvesting, are community-driven and accompanied by cultural celebrations. Historically linked to ancient slash-and-burn practices without involving livestock's dating back thousands of years, Podo farming continues to sustain tribal groups such as the Gond, Maria, and Muria.

## Working of Podo System

Podo farming relies on natural ecological processes rather than external inputs. Farmers select a small patch of forest land, clear shrubs and smaller vegetation, and allow the biomass to dry. Prior to the monsoon, the dried material is burned, producing ash that enriches the soil with nutrients. Seeds are sown directly into the ash-enriched soil using simple tools, and crops depend entirely on rainfall. After two to three years of cultivation, the land is left fallow for more than 10 years to naturally regenerate. Over time, soil fertility is restored, enabling reuse after a sufficient recovery period.

## Operational Practices

Podo farming is very closely synchronized to the natural seasonal periods and incorporates entire family and villages to produce under the system (Table 1 & Fig.1).

### Site Selection and Land Preparation

Elders in the community identify suitable sites based on slope and ecological conditions during winter months. Vegetation clearing is carried out manually, usually retaining larger trees. Controlled burning ensures nutrient recycling while minimizing forest damage.

### Sowing and Harvesting

Sowing begins with the onset of monsoon rains. Farmers use simple tools such as sticks to place seeds, avoiding soil disturbance. Crops mature at different times, ensuring a continuous food supply from October to December.

### Crop Diversity

A key strength of the Podo system is mixed cropping. Multiple crops are cultivated together to reduce risk and enhance food security.

**Millets:** Staple crops such as kodo and kutki, valued for their resilience and nutrition

**Legumes:** Beans and peas that improve soil fertility

**Vegetables and Tubers:** Provide dietary diversity and act as fallback food sources

**Table1: Comparative account on podo and other similar farming systems of India**

| Farming system | Region & community practices | Process / Characteristics | Crops cultivated | Community Aspect |
|---|---|---|---|---|
| Podo | Bastar, Chhattisgarh and typically associated with tribes like Gond, Maria and Muria | Clearing forest patch, burning dry brush, ash fertilizer, rain-fed mixed cropping, short cultivation (2-3 years), abandonment, long fallowing for regeneration (ideally 10-15+ years). | Cultivate diverse mix of millets, pulses, vegetables, and tubers. | Strong community labour sharing, rituals, and festivals (e.g., Mati Tihaar, Madai) celebrating planting and harvest. |
| Bewer (Bewar) | Central India and associated Baiga tribe | Clearing, burning, ash fertilization, mixed cropping, short cultivation, abandonment, long fallowing. | Identical high diversity of millets, pulses, vegetables, and tubers | Similar strong community effort, spiritual connection, rituals surrounding fire/earth. |
| Jhum | Northeast India and various communities | Clearing, burning, ash fertilization, mixed cropping, short cultivation, abandonment, long fallowing. | Identical high diversity of millets, pulses, vegetables, and tubers, fundamentally the same polyculture. | Crucial for community food security, deep cultural ties, community participation in farming activities. |

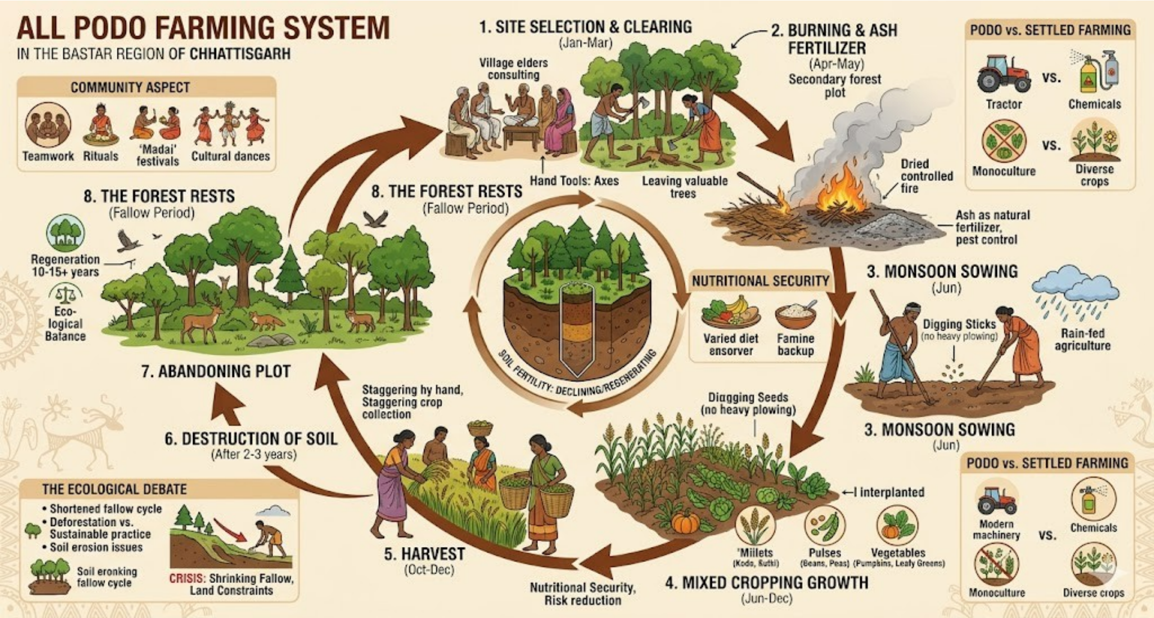

Fig.1: Ancient Podo Farming System prevalent practicing in Baster region of Chhattisgarh.

### Ecological and Societal Significance

Podo farming promotes ecological balance by avoiding chemical inputs and allowing natural forest regeneration during fallow periods. It also strengthens community bonds through shared labour and cultural practices.

Modern adaptations suggest integrating trees like mango, bamboo, and jackfruit within farming systems to enhance sustainability and income. Additionally, increasing demand for traditional millets is improving livelihoods for tribal farmers.

### Podo System: A Novel Form of Natural Farming Approach without Animal-Based Inputs

The traditional Podo farming system is increasingly recognized for its ecological sustainability. When practiced with adequate fallow periods of 10–15 years, the system allows complete natural regeneration of the forest ecosystem. During this resting phase, soil fertility is restored, biodiversity returns, and wildlife re-establishes itself. Moreover, the absence of chemical inputs ensures that surrounding water bodies remain unpolluted, maintaining overall environmental health.

### Integration of Trees with Cropping Systems

A promising adaptation of the Podo system involves integrating trees with crops. Instead of leaving cultivated slopes entirely fallow, farmers can plant multipurpose tree species such as mango, jackfruit, and bamboo alongside crops. These trees help in soil conservation by stabilizing slopes and reducing erosion. Additionally, they provide long-term economic benefits through the sale of fruits and bamboo, thereby reducing the need to clear new forest areas.

### Revival of Traditional Millets

There is a growing recognition of the nutritional and ecological value of traditional millets such as kodo and kutki. These resilient crops, traditionally cultivated in the ash-enriched soils of Bastar, are gaining popularity in urban markets. Government procurement at remunerative prices has further encouraged tribal farmers to continue cultivating these climate-resilient and nutritionally rich crops, supporting both livelihoods and sustainable agriculture.

### Balancing Tradition with Modern Needs

Podo farming reflects a deep understanding of ecological processes and a respectful relationship with nature. Labeling it as “backward” overlooks its scientific and cultural significance. At the same time, contemporary challenges such as deforestation require thoughtful interventions. Sustainable solutions lie in engaging with local communities, respecting their traditional knowledge and land rights, and supporting them in adopting improved, environmentally sound practices that enhance soil health and productivity.

### Conclusion

The Podo farming system represents a sustainable and culturally rich agricultural practice based on coexistence with nature. In the face of climate change and environmental degradation, such indigenous knowledge systems offer valuable lessons in resilience and sustainability. Protecting and refining these practices through community engagement and scientific support is essential for future food and ecological security.

ISSN : 2583-0910
Agri-India TODAY
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Peer reviewed
monthly newsletter

Article ID : 06/VI/27/0626

# COLLECTIVE STRENGTH: HOW FPOS ARE REWRITING THE STORY OF THE INDIAN FARMER

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The survival of the small-scale farmer has long been a story of grit against impossible odds. In India, where more than 85% to 86% of farmers work on small and marginal holdings often less than two hectares the deck is stacked heavily against the individual. These farmers face a "triple threat": high production costs, crumbling market access and a lack of bargaining power. This leaves them vulnerable to monopolistic exploitation and dependency on middlemen. However, a quiet revolution is taking root through Farmer Producer Organizations (FPOs) a model that seeks to replace individual struggle with collective strength.

## Beyond the ghost of cooperatives

For many, the idea of "farmer collectives" brings to mind the old cooperative societies that have been part of the Indian landscape since 1904. While some were legendary successes, many others withered under the weight of mismanagement, political interference and restricted regional operations. The FPO is designed to be different a "hybrid" that combines the social heart of a cooperative with the business brain of a private company. By registering as Producer Companies (PCs) under the Companies Act, these groups gain a legal identity that allows them to process, brand, and export goods with corporate efficiency while keeping farmers as the sole owners and beneficiaries. Unlike traditional cooperatives, FPOs are designed as self-governing, stand-alone bodies to minimize the "village level politics" and bureaucratic hurdles that historically slowed progress.

**Table 1 : Comparison Between Traditional Cooperatives and Farmer Producer Companies**

| Parameter | Cooperative Society | Producer Company (FPO) |
|---|---|---|
| Registration | Cooperative Societies Act | Indian Companies Act |
| Area of Operation | Restricted/Discretionary | Entire Union of India |
| Government Control | Highly patronized/interfered | Minimal/Statutory only |
| Profit Sharing | Limited dividends on shares | Based on volume of business |

## Strength in Numbers: The Economic shift

The primary goal of an FPO is simple: enhance competitiveness and ensure better income through an organization the farmers own. When farmers aggregate, the math of farming changes. Instead of buying expensive seeds and fertilizers in small packets, they procure in bulk at wholesale rates, slashing their cost of cultivation. On the selling side, they move from being "price takers" to "price makers". By pooling their produce, they can afford the technology to grade, process, and package their goods, turning raw crops into high-value products that reach consumers more directly.

## Key Services and Success Stories

- Comprehensive Support: FPOs provide critical services including input supply, procurement and technical training.

- Global Reach: In Maharashtra, the Mahagrapes collective has become a global marketing partner, proving that smallholders can compete in high-end export markets through public-private partnerships.
- Market Formidability: The Vasundhara Agri-Horti Producer Company (VAPCOL) has shown how collective action can turn a fragmented group of growers into a formidable market competitor.
- Efficiency: The case of Avirat in Gujarat highlights how FPOs significantly reduce transaction costs and eliminate the middleman.

**Case Study: The "Tomato Revolution" of Narayangaon**

The Challenge: Exploitation and Perishability Before forming the FPO, tomato growers in Narayangaon faced severe hardship. Because tomatoes are highly perishable, farmers were forced to sell at any price offered by middlemen, who often provided false market information, delayed payments, and deducted arbitrary fees for "accidental losses" during transport. Despite their hard work, the farmers saw almost no profit.

The Turning Point: Collective Action In 2013-14, leader Shriram Gadhve mobilized the community, convincing growers to join the FPO movement supported by the Vegetable Growers Association of India (VGAI) and the Small Farmers Agribusiness Consortium (SFAC). They formed the Junnar Taluka Farmers' Producer Organization and Producer Company with 1,600 members and a modest share capital of Rs. 5 lakh.

The Transformation: From "Price Takers" to "Price Makers" The FPO successfully broke the chain of exploitative intermediaries by establishing its own wholesale auction market in Narayangaon. The impact was immediate and profound:

- National Hub: Narayangaon is now the largest open tomato auction market in India, attracting traders from major cities like Delhi, Mumbai, Bangalore and Chennai.
- Instant Prosperity: Merchants now pay farmers in cash on the spot. This has led to all-around prosperity; many farmers now live in permanent "pukka" houses, own cars, and can afford higher education for their children.
- Scaling Up: Cultivation expanded from 500 acres across 50 villages to 2,200 acres across 150 villages.
- Technological Gains: Members now use advanced technologies like mulching paper (increasing yields 3-4 times) and low-cost drip irrigation (costing Rs. 8,000-12,000 per acre compared to the normal Rs. 25,000).

**Beyond Tomatoes: Diversified Services**

The company has since expanded into other high-value activities:

- Common Purchasing: Buying seeds directly from companies saves members 25% to 30%.
- Contract Farming: They have secured buy-back contracts with major firms like ITC for potato cultivation.
- Direct Marketing: The FPO operates its own vegetable selling center, moving 5-6 metric tons of fresh produce directly to consumers daily.

**The Road Ahead: Growth Pains and Potential**

Despite the momentum with thousands of FPOs established through nodal agencies like SFAC and NABARD the path is not without hurdles. Many FPOs currently struggle with "business illiteracy".

Running a registered company requires skills in accounting, inventory management and strategic planning that many farmers haven't yet mastered.

There is also a desperate need for "patient capital" long-term financial support that stays with the FPO for four to five years to ensure they become truly viable. To help these groups succeed, the government has introduced significant reforms:

- **Tax Holidays:** A 100% tax holiday for FPOs with a turnover below 100 crores for up to five years.
- **Specialized Credit:** Facilities like the "Producers Development and Upliftment Corpus (PRODUCE)" have been established.
- **Policy Linkages:** Combining support with direct linkages to retailers and the corporate sector is essential for a profitable ecosystem.

The future lies in moving beyond simple aggregation toward sophisticated value-addition, unique branding for local crops, and securing quality certifications.

### A New Chapter For Rural India

FPOs are more than just a business model; they are a vehicle for social empowerment. When a smallholder joins an FPO, they are no longer an isolated player in a volatile global market. They become part of a professional network that offers technical advice, credit linkages, insurance, and a collective voice.

If we can bridge the gap in management skills and ensure steady policy support, the FPO could very well be the institutional innovation that finally secures the income and dignity of the Indian farmer.

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ISSN : 2583-0910
Agri-India TODAY
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Peer reviewed
monthly newsletter

Article ID : 06/VI/28/0626

# BIODEGRADABLE SEQUINS IN THE TEXTILE INDUSTRY: SPARKLE WITH SUSTAINABILITY

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## Abstract

The growing concerns about the environment related to plastic-based textile decorations have created a pressing need for sustainable alternatives in the fashion and apparel industry. Traditional sequins, commonly found in clothing and accessories, are mainly made from petroleum-based polymers like polyvinyl chloride and polyethylene terephthalate. These materials add to waste that does not decompose and contribute to microplastic pollution. Sustainable sequins, made from biodegradable, compostable, recycled, or bio-based materials, are coming forward as a promising option. This article looks at the future of sustainable sequins, focusing on new materials, manufacturing methods, market trends, environmental benefits, challenges, and opportunities, especially within the Indian textile industry. The blend of scientific advancements with design shows that sustainable sequins could significantly impact the shift toward circular and responsible fashion.

**Keywords:** Cellulose-Based Sequins, Conventional sequins, Seaweed Based Sequins, Sustainable sequins

## Introduction

The textile and fashion industry is one of the most dynamic industries in the world. They have an impact on culture, identity, creativity, and economic growth. On the other hand, this industry is very resource-intensive and environmentally challenging. These include water contamination, high energy use, greenhouse gas emissions, chemicals and waste created during and after consumption of items made from textiles. In addition to fabric, the use of decorative elements used on textiles (i.e. decorations or accessories) has come under criticism for being unfriendly to the environment. Recently, an important trend occurring within the textile and clothing industry has been the increased demand for sustainable and environmentally friendly products. As consumers become more aware of environmental issues, they are purchasing not only fashionable but also socially responsible products. In this context of greener fashion, biodegradable sequins have gained attention.

Sequins are widely used as the decorative elements for clothing. They are small reflective discs attached to fabric surfaces to enhance aesthetic appeal. Sequins are common in evening wear, bridal garments, festive clothing, stage costumes, children’s wear, handbags, footwear, and home furnishings. Their popularity lies in their ability to create shine, glamour, texture, and visual dynamic appearance. Traditionally, sequins are manufactured using plastic materials such as polyvinyl chloride (PVC), polyethylene terephthalate (PET), or even metallic-coated films. Even though these sequins look appealing to consumers, their use creates significant environmental issues due to their inability to degrade easily. Plastic sequins take decades to break down into smaller pieces inside landfills.

When garments with plastic sequins are washed, tiny particles may break off and enter water systems as microplastics. These microplastics can harm marine life, pollute rivers and oceans, and eventually enter the food chain. As millions of fashion products are produced every year, decorative plastic trims like sequins contribute significantly to textile waste. Sustainable sequins have been identified as a modern alternative that helps in reducing the harmful impacts of sequins. Sustainable sequins represent a new generation of decorative materials designed to maintain visual attractiveness while minimizing ecological harm.

The main benefit of sustainable sequins is that they help to promote sustainable fashion practices. Sustainable fashion tries to minimize waste and make products from resources in a way that is environmentally friendly. By replacing plastic sequins with biodegradable options, designers can create attractive garments that are more eco-conscious.

### What Are Sustainable Sequins?

Sustainable sequins mean the embellishments which are produced through environmentally friendly materials or processes during the entire life cycle of the products. The aim of using sustainable sequins is to substitute petroleum-based trims by sustainable, recyclable, and biodegradable products or other similar sustainable materials. There are numerous applications for the use of sustainable sequins because they are versatile products. Nowadays fashion designers are actively exploring new trends of biodegradable sequins due to changed consumer needs.

### Types of sequins

There are various types of biodegradable sequins depending upon the type of raw material, appearance, and application in textile goods. The main types of sustainable sequins are given below:

#### 1. Cellulose-Based Sequins

These are some of the most popular types of biodegradable sequins that can be found and they are derived from cellulose that is extracted from wood pulp, cotton fibers, or other forms of agricultural waste. These are abundant, renewable, biodegradable, and can form clear films. The cellulose sequins are one of the best sequin alternatives available today.

#### 2. Polylactic Acid (PLA)

PLA is an eco-friendly thermoplastic made from fermenting plant sugars like corn starch or sugarcane. These can be used to make filmic and ornamental shapes. They are biodegradable in industrial composting and light-weight with high transparency. They have good properties and PLA sequins are ideal for use in fashion clothing items or accessories.

#### 3. Starch-Based Polymers

Sequins made using the starches of maize, tapioca, potato, or cassava may be mixed with plasticizers and other biodegradable agents to produce sequin fabrics. Such sequins are biodegradable and economical. These are usually used in fashion clothes and items that are to be used for limited periods only.

#### 4. Protein-Based Materials

They are made from gelatin and natural proteins. Prior to the use of plastic, these were widely used in fashion industries. They are biodegradable but are fragile and prone to damage from moisture or heat.

#### 5. Cellulose Acetate Sequins

They are manufactured using cellulose and offer higher durability, transparency, and aesthetic qualities than traditional sequins. They are generally called eco-friendly sequins.

#### 6. Recycled Materials

Sequins are produced from the polymers of recycled PET water bottles or other textile polymer wastes. Such sequins are not biodegradable, but they ensure better resource management and reduced dependence on plastics.

### 7. Seaweed / Algae-Based Sequins

They are innovative, eco-friendly sequins produced from marine biomass and seaweed extracts. They decompose naturally and have potential applications in the manufacturing of sustainable luxury fashion items.

### 8. Compostable Bio-Composite Sequins

These sequins are composed of biodegradable polymers and natural fibres or fillers, including bamboo powder, rice husk, and agricultural waste.

### Benefits Over Traditional Sequins

The transition from traditional petroleum-based sequins to sustainable alternatives represents a major shift in material science. For the fashion industry, particularly for high-embroidery countries such as India, this shift offers many advantages apart from merely safeguarding the environment as well as more aesthetically pleasing and economically feasible. These are some of the key advantages offered by sustainable sequins in contrast to conventional PVC/PET sequins.

### 1. Environmental Impact and Circularity

- **Biodegradability:** Traditional sequins are "forever plastics" that take 200–500 years to decompose. The sustainable sequins, especially those made from cellulose or seaweed, can be decomposed industrially or even at home within months.
- **Elimination of Microplastics:** Every time the traditional sequin garment is washed or worn, it sheds small plastic fragments. Sustainable sequins are derived from organic polymers which biodegrade to produce organic waste, thus eliminating the problem of micro-plastic pollution in the seas and food chain.
- **Lower Carbon Footprint:** The conventional sequins are extracted from crude oil. The sustainable sequins, however, use renewable material such as algae and wood pulp. The algae and wood pulp serve as carbon sinks during the growth stage, greatly minimizing the carbon footprint of the fabric.

### 2. Human Health and Safety

- **Non-Toxic Composition:** While the traditional sequins consist of PVC that is laced with phthalates to give it the flexibility required and heavy metals like lead or cadmium for the metallic luster. The sustainable sequins incorporate non-toxic and bio-based resin and natural minerals for shimmer, making them safer for both the garment workers handling them and the end consumer.
- **Hypoallergenic Properties:** Natural materials are generally more skin-friendly. In cases where the sequined garments will come into contact with the skin, such as in the case of heavy bridal gowns or evening gowns, bio-based materials minimize the risk of contact dermatitis or irritation caused by synthetic chemical coatings.

### 3. Aesthetic and Design Innovations

- **Structural Coloration:** Many sustainable sequins (like BioSequin™) use structural color rather than synthetic dyes. This creates a more "alive," multidimensional shimmer that mimics nature (like the wings of a butterfly) which traditional flat-plastic dyes cannot perfectly replicate.
- **Weight Reduction:** Bio-based sequins, especially those made from seaweed or thin cellulose films, are often significantly lighter than plastic or metal-backed sequins. This allows

designers to create heavily embellished garments that are more comfortable and put less strain on the base fabric.

- **Unique Textures:** Sustainable materials offer a range of finishes from matte "stone-look" textures to high-gloss translucent finishes that provide a "premium and artisanal" feel, differentiating high-end fashion from mass-produced plastic garments.

**4. Economic and Brand Value**

- **Meeting "Gen Z" Demand:** In 2026, market data shows that younger consumers are actively seeking transparency. Brands using sustainable sequins can command a "green premium" and build stronger brand loyalty by offering verifiable eco-friendly credentials.
- **Future-Proofing against Regulation:** Governments worldwide (including India's Ministry of Environment) are increasingly cracking down on single-use plastics and hazardous chemicals in textiles. Switching to sustainable embellishments now protects manufacturers from future bans on PVC or specific synthetic dyes.
- **Waste Valorization:** Many sustainable sequins are made from waste. This turns a disposal cost into a value-added product, supporting a circular economy within the textile supply chain.

**5. Durability and Performance**

- **Improved Heat Resistance:** While some bioplastics are sensitive, high-quality cellulose-based sequins can actually offer better heat resistance than low-grade PVC, which can melt or warp during the ironing or steam-pressing stages of garment finishing.
- **Light-Fastness:** Modern bio-sequins are engineered with natural UV stabilizers, ensuring that the sparkle doesn't fade or "yellow" over time, a common issue with cheap plastic sequins exposed to sunlight.

**Challenges**

- **Moisture Sensitivity:** Many bio-based polymers (like seaweed alginate or starch-based films) are naturally hydrophilic. Exposure to humidity, sweat or liquid spills can cause them to soften, warp or lose their shimmer.
- **Laundering Constraints:** Traditional dry-cleaning chemicals and machine washing provide a harsh environment. Cellulose-based sequins often struggle to maintain their structural integrity during repeated aqueous laundering without the use of toxic synthetic coatings which would defeat their purpose.
- **Production Waste:** Sequin production is a subtractive process; punching circles from a sheet creates material scrap. While bio-waste can be composted, the energy cost of producing the initial film makes this waste more expensive than with cheap plastics.
- **Aesthetic Limitations:** Achieving vibrant, iridescent colors without using heavy metals (like lead or cadmium) or synthetic dyes is difficult. Creating a high-gloss, reflective surface typically requires a coating; finding a 100% bio-based resin that provides "mirror-like" shine remains a top research priority.
- **Infrastructure Gaps:** A lack of widespread industrial composting sites to ensure the "end-of-life" cycle is actually completed. For many bio-sequins (like PLA), degradation only occurs in **industrial composting** facilities. If a consumer tosses a "biodegradable" garment into a standard landfill, the lack of oxygen and microbes may prevent it from breaking down as intended.

## Future of biodegradable sequins

The future of sustainable sequins is highly promising as the textile and fashion industry shifts toward environmentally responsible materials. Traditional plastic sequins are increasingly criticized for contributing to landfill waste and microplastic pollution, creating strong demand for biodegradable and circular alternatives. Several innovators are already commercializing plant-based or plastic-free sequins made from cellulose and other renewable materials, showing that sustainable sparkle is moving from concept to market reality.

In countries like India, where festive and decorative clothing has a large market, biodegradable sequins can play an important role. They can help combine traditional beauty with modern sustainability. A major future trend will be the use of bio-based raw materials which can reduce dependence on fossil-fuel plastics while lowering carbon emissions. Research partnerships are also working on scaling commercially viable biodegradable sequins that maintain shine, durability and wash performance. Another important direction is the circular fashion model. Future sequins are expected to be designed for easier recycling, composting or safe degradation at end-of-life. Instead of being permanent plastic trims attached to garments, they may become detachable, reusable or biodegradable components that align with zero-waste fashion systems.

## Conclusion

Biodegradable sequins are an excellent example of how fashion can combine beauty with responsibility. By replacing persistent petroleum-based plastics with innovative bio-polymers such as plant-derived cellulose and seaweed-based bioplastics the apparel sector is directly addressing the microplastic crisis. They offer the sparkle and elegance of traditional sequins without causing the same level of environmental harm. For a global embroidery hub like India, this transition offers a unique opportunity to modernize traditional embroideries, aligning ancient artistry with futuristic, non-toxic material science. Although improvements in cost and durability are still needed, these eco-friendly embellishments represent a major step toward a cleaner and more sustainable textile industry. In the coming years, biodegradable sequins may become the preferred choice for fashion that shines responsibly.

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ISSN : 2583-0910

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Peer reviewed
monthly newsletter

Article ID : 06/VI/29/0626

# SNIFFER BEE TECHNOLOGY: THE FUTURE OF BIO-DETECTION

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## Abstract

Sniffer bee technology is an emerging bio-detection approach that utilizes the highly sensitive olfactory system of honey bees (*Apis mellifera*) for detecting specific chemical compounds. Bees can perceive odors at extremely low concentrations and can be rapidly trained through classical conditioning techniques such as the Proboscis Extension Response (PER). By associating target odors like explosives, narcotics or disease-related volatile compounds with a food reward, bees become efficient biological sensors. The operational framework of this technology includes conditioning, deployment, tracking and mapping, where trained bees actively search for odor sources and their movement patterns are analyzed using advanced tools like UAVs and LIDAR. This technology has diverse applications, including landmine detection, environmental monitoring, disease diagnostics and precision agriculture. Compared to conventional methods, sniffer bees offer advantages such as low cost, rapid training, wide-area coverage and minimal risk to human life. However, limitations such as environmental dependency, behavioral variability and challenges in tracking remain. Overall, sniffer bee technology presents a promising, eco-friendly alternative for future detection systems.

**Keywords :** Honey bees, Biological Sensor, Sniffer bee technology, LIDAR, Explosive detection

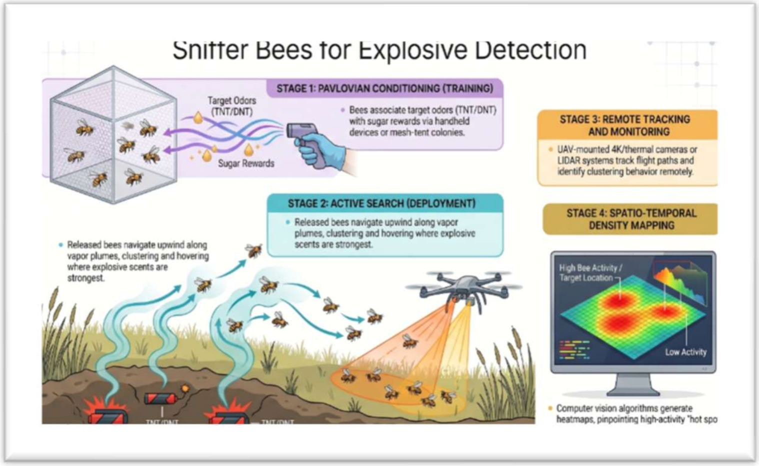
## Introduction

Honey bees (*Apis mellifera* L.) are well known for their role in pollination, but their highly developed olfactory system has attracted attention for use as biological sensors. Studies have shown that honey bees can detect a wide range of chemical compounds at extremely low concentrations, even at parts-per-trillion levels (Bromenshenk *et al*., 2003; Rodacy *et al*., 2002). This exceptional sensitivity forms the basis of sniffer bee technology, where bees are utilized for detecting specific odors of interest. The principle of this technology relies on the ability of honey bees to learn and associate odors with rewards through classical conditioning methods such as the Proboscis Extension Response (PER) (Bitterman *et al.,* 1983). Once trained, bees can recognize and respond to target chemicals, making them useful for detecting substances such as explosives, pollutants and other volatile compounds. Compared to conventional detection methods, bees offer advantages such as rapid training and the ability to cover large areas efficiently (Marshall, 1935).

Initial research, particularly during the late 1990's and early 2000's, demonstrated the feasibility of using bees for detecting explosive vapors, including TNT and DNT, with high accuracy under field conditions (Rodacy *et al*., 2002). Additionally, their natural foraging behavior allows them to collect environmental samples, making them useful for monitoring chemical contamination over wide areas. Although the technology is still developing, sniffer bee systems represent a promising, cost-effective and eco-friendly approach for chemical detection (Bromenshenk *et al.,* 2003). Further details on their working mechanisms, applications and limitations are discussed in subsequent sections (Gillanders *et al.,* 2021).

**Concept and Working flow of Sniffer Bee Technology:**

Sniffer bee technology relies on the honey bee's extraordinary olfactory system, which can detect odors at parts-per-trillion levels and their natural capacity for associative learning (Bromenshenk *et al.,* 2003). Through classical Pavlovian conditioning, bees are taught to associate a specific target scent (such as explosives, narcotics or diseases) with a sugar reward, effectively turning them into highly sensitive, living biological sensors. The active implementation of this technology generally follows a four-stage process involving conditioning, deployment, tracking and mapping. Initially, during the conditioning phase, bees are trained through classical conditioning by repeatedly exposing them to a specific target odor, such as TNT vapor, followed immediately by a sucrose reward, enabling associative learning (Simić M *et al*., 2019). This training can be conducted either on individual bees using controlled laboratory devices or on entire colonies within enclosed setups like mesh tents. Subsequently, in the active search or deployment phase, the trained bees are released over suspected areas such as minefields, where, driven by their natural foraging behavior, they detect and follow odor plumes upwind toward the source, exhibiting increased hovering and aggregation at points of highest odor concentration (Rodacy *et al*., 2002).



In the tracking phase, due to the small size and rapid movement of bees, their flight patterns and clustering behavior are monitored using advanced remote sensing technologies such as Light Detection and Ranging (LIDAR) systems or Unmanned Aerial Vehicles (UAVs) equipped with high-resolution optical and thermal imaging sensors (Das *et al.,* 2026). Finally, in the mapping phase, the collected spatial and temporal data are analyzed using computer vision algorithms to generate spatio-temporal density maps, where regions with a high concentration of bee activity accurately indicate the precise locations of concealed targets.

**Applications of Sniffer Bee Technology**

1. **Explosives & Landmine Detection:** Trained bees detect vapours of TNT, DNT, RDX and help in minefield surveying, hazard detection and post-clearance verification with high accuracy (Rodacy *et al*., 2002).
2. **Narcotics & Contraband Screening:** Bees can identify drugs like cocaine, heroin, amphetamines and cannabis, making them useful for cargo and security screening (Schott *et al*., 2015)
3. **Disease Diagnostics (Human/Animal):** Bees detect disease-related volatile compounds, helping in diagnosing conditions like tuberculosis, cancer and viral infections. (Suckling and Sagar, 2011; Kontos *et al*., 2022; Parnas *et al.,* 2024)

4. **Plant Disease Detection:** Used in agriculture to identify early pest infestations or infections, such as larvae inside fruits. (Chamberlain *et al*., 2012)
5. **Environmental pollution and nuclear contamination tracking:** Free-flying bees collect pollutants from air, water and plants, allowing large-scale environmental assessment. Honeybees and their byproducts have been used as sensitive indicators of nuclear pollution following the Chernobyl disaster (Barisic *et al*., 2002).
6. **Precision Agriculture (Targeted Pollination):** Bees can be directed to specific crops to improve pollination and increase crop yield. (Twidle *et al*., 2015)
7. **Food Quality Control:** Used to differentiate between pure and adulterated honey or identify floral origin. (Bonod *et al*., 2003)

**Advantage of Sniffer bee technology:** Rapid training, cost-effectiveness, autonomous operation, minimal risk of triggering landmines, no requirement of human handlers and suitability for stealth operations.

**Limitations**: Inability to detect odorless chemicals, chances of misidentification, behavioral inconsistency, tracking difficulties, dependence on weather conditions and need for continuous training.

## Conclusion

Sniffer bee technology represents a novel and promising advancement in the field of biological detection, leveraging the exceptional olfactory sensitivity and learning ability of honey bees. Through simple conditioning techniques bees can be rapidly trained to detect a wide range of chemical compounds offering a cost-effective, efficient and eco-friendly alternative to conventional detection systems. Its wide applicability in areas such as landmine detection, disease diagnostics, environmental monitoring and precision agriculture highlights its multidisciplinary significance. Despite certain limitations, including environmental dependency, behavioral variability and tracking challenges, ongoing technological improvements are likely to enhance its reliability and field applicability. Overall, sniffer bee technology holds great potential as an innovative bio-sensing tool and may play a crucial role in future detection and monitoring systems with further research and refinement.

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ISSN : 2583-0910
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monthly newsletter

Article ID : 06/VI/30/0626

# SPATIAL MAPPING OF ENVIRONMENTAL NUCLEIC ACIDS (eDNA/eRNA) USING GIS FOR ADVANCED FISHERIES RESOURCE MANAGEMENT

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The landscape of Fisheries Resource Management (FRM) is rapidly evolving, shifting from traditional, labour-intensive catch surveys to high-precision, non-invasive digital and molecular monitoring. Among the most transformative of these advancements is the integration of Geographic Information Systems (GIS) with the analysis of environmental nucleic acids, specifically environmental DNA (eDNA) and environmental RNA (eRNA). While eDNA and eRNA provide the biological "what" and "how much" regarding aquatic populations, GIS provides the crucial "where." By synthesizing these disciplines, fisheries managers can construct real-time, highly accurate spatial models of aquatic ecosystems, leading to more sustainable and responsive management strategies.

## The Molecular Frontier: From eDNA to eRNA

Environmental DNA analysis has revolutionized biomonitoring by allowing scientists to detect species presence simply by analysing the genetic material shed into the water column through scales, mucus, and feces (Ficetola *et al.*, 2008). This method has proven invaluable for detecting rare or invasive species that are difficult to locate using traditional netting or electrofishing (Thomsen & Willerslev, 2015). However, a significant limitation of eDNA in spatial management is its persistence in the environment. Because DNA is a highly stable molecule, it can remain in water or sediment long after an organism has died or migrated, potentially leading to false-positive distributions and complicating real-time habitat mapping (Barnes & Turner, 2016).

This limitation is driving the frontier of FRM toward environmental RNA (eRNA). Unlike its DNA counterpart, RNA degrades rapidly upon leaving the host organism. Therefore, the detection of eRNA in a water sample is a strong indicator of the recent, active presence of living aquatic communities (Wood *et al.*, 2020). For fisheries managers attempting to monitor real-time ecosystem shifts, developmental programming, or immediate responses to environmental stressors, eRNA provides a much higher temporal resolution.

## Integrating GIS: Mapping the Invisible

To harness the full potential of these molecular tools, they must be grounded in geographic reality. This is where GIS becomes indispensable. Detecting a sequence of eRNA is only half the battle; understanding where that genetic material originated, how it dispersed, and what environmental factors influenced its degradation requires complex spatial modelling (Carraro *et al.*, 2020).

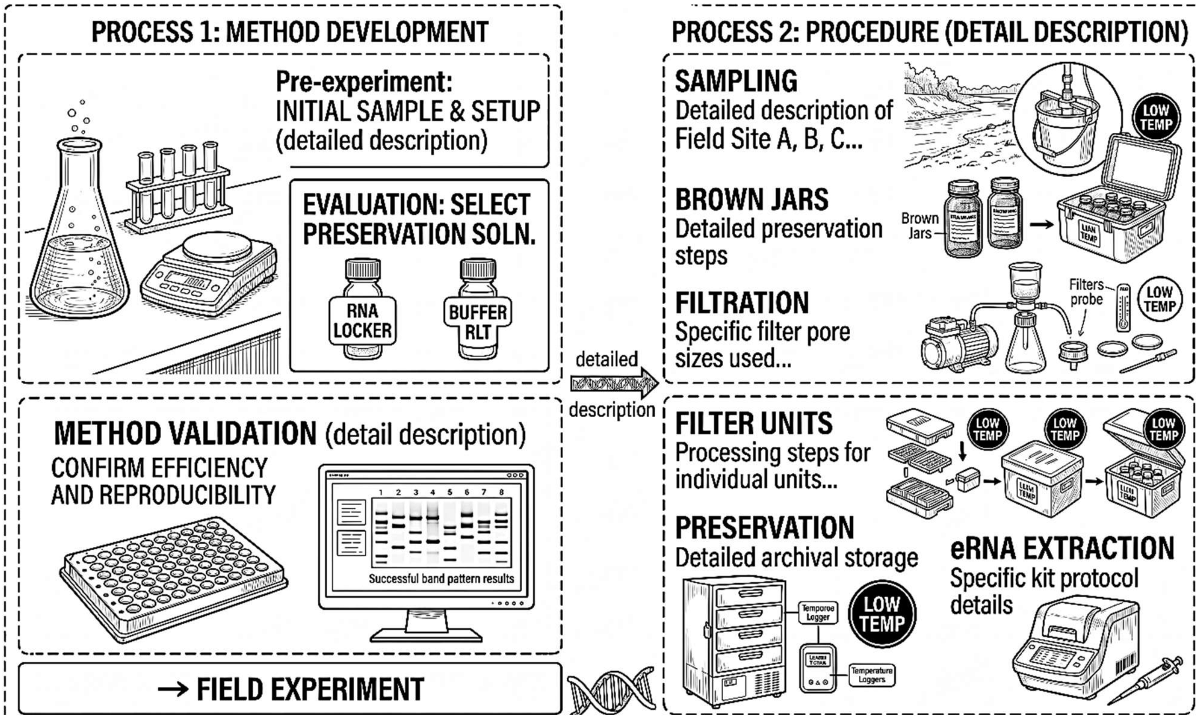
GIS software allows researchers to overlay molecular data onto detailed topographical and hydrological maps. When water samples are collected across a river network or a landlocked canal system, GIS can map the concentration gradients of eDNA and eRNA. By integrating variables such as water velocity, temperature, and localized IoT sensor data into the GIS framework, spatial models can trace the genetic signal backward to pinpoint the exact location of the target fish population (Deiner *et al.*, 2017).

For instance, if managers are tracking the migration of an endangered teleost species, taking spatially explicit eRNA samples and plotting them on a GIS dashboard reveals not just that the fish are in the river system, but precisely which tributaries they are currently utilizing for spawning. This level of spatial resolution is critical for dynamic, highly targeted conservation efforts.

**Applications in Precision Fisheries Management**

The practical applications of GIS-integrated eRNA and eDNA mapping in FRM are vast. First, it enables highly precise invasive species management. By mapping the leading edge of an invasion front using eRNA, managers can deploy localized containment strategies before the species becomes established, rather than applying broad, ecologically disruptive eradication methods across an entire water body.

Secondly, this integrated approach allows for the spatial modelling of phenotypic plasticity and stress responses. By comparing eRNA transcriptomic yields against GIS maps of water quality-such as areas with high agricultural runoff or localized temperature spikes-researchers can visually map how different geographic zones are triggering epigenetic stressors in fish populations. This gives policymakers the spatial evidence needed to regulate specific land uses that negatively impact adjacent fisheries (figure 1).



**Conclusion**

The future of Fisheries Resource Management lies at the intersection of molecular biology and spatial technology. By moving beyond simple geographic mapping and incorporating the real-time transcriptomic yields of eRNA, GIS frameworks are becoming dynamic dashboards of aquatic ecosystem health. For researchers and managers navigating the complexities of modern aquatic environments, mastering the synergy between spatial analytics and environmental nucleic acids is no longer optional; it is the new standard for sustainable fisheries management.

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ISSN : 2583-0910
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Peer reviewed
monthly newsletter

Article ID : 06/VI/31/0626

# STATUS OF BANNED AND RESTRICTED PESTICIDES IN INDIA AND THEIR AGRICULTURAL IMPACT

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## Abstract

Pesticides play an important role in protecting crops from insect pests, diseases, and weeds, thereby improving agricultural productivity and food security. However, excessive and indiscriminate use of hazardous pesticides has caused environmental contamination, pesticide residues, pest resistance, and health hazards to humans and animals. In India, pesticide regulation is managed by the Central Insecticides Board and Registration Committee (CIB&RC) under the Insecticides Act, 1968. Several pesticides including Aldrin, Endosulfan, Carbaryl, Dicofol, and Paraquat Dimethyl Sulphate have been banned or restricted due to their toxicological and ecological risks. This article reviews the current status of banned and restricted pesticides in India and their agricultural impacts. It also highlights the importance of bio-pesticides and Integrated Pest Management (IPM) strategies for sustainable agriculture.

**Keywords:** Banned pesticides, restricted pesticides, India, pesticide regulation, sustainable agriculture, environmental impact, IPM

## Introduction

Pesticides are extensively used in modern agriculture for the management of insect pests, diseases, weeds, rodents, and storage pests, thereby contributing significantly to crop protection and food security. India is among the major consumers of pesticides in agriculture due to increasing food demand and intensive cultivation practices in crops such as rice, cotton, vegetables, pulses, and oilseeds. However, excessive and indiscriminate use of pesticides has led to environmental contamination, pesticide residues in food, bioaccumulation, decline of beneficial organisms, and adverse effects on human and animal health (Sharma *et al.,* 2019; WHO, 2020). Persistent pesticides, particularly organochlorines and organophosphates, are associated with long-term ecological and toxicological risks because of their persistence and harmful effects on non-target organisms.

To minimize these hazards, the Government of India regulates pesticide use through the Central Insecticides Board and Registration Committee (CIB&RC) under the Insecticides Act, 1968. Several hazardous pesticides including Aldrin, Endosulfan, Lindane, Methyl Parathion, Phorate, and Triazophos have been banned, restricted, or withdrawn due to concerns related to toxicity, carcinogenicity, environmental persistence, and bioaccumulation. In recent years, increasing emphasis has been placed on safer alternatives such as bio-pesticides and Integrated Pest Management (IPM) practices for sustainable agriculture and environmental protection (CIB&RC, 2024; WHO, 2020).

## Pesticide regulation in India

Pesticide regulation in India is governed by the Insecticides Act, 1968 and the Insecticides Rules, 1971. The Central Insecticides Board and Registration Committee (CIB&RC) is responsible for pesticide registration, approval of formulations, monitoring pesticide safety, and restricting or banning hazardous chemicals harmful to humans and the environment. The Central Insecticides Board (CIB) advises the government on pesticide safety and risk management, while the Registration Committee (RC) evaluates pesticides based on efficacy, toxicity, residue behaviour, and environmental impact before approval.

India permits several major pesticide groups for agricultural use, including organophosphates, pyrethroids, neonicotinoids, and carbamates for the management of insect pests and diseases. Along with conventional pesticides, the Government of India is increasingly promoting eco-friendly alternatives such as neem-based formulations and microbial bio-pesticides including *Bacillus thuringiensis*, *Beauveria bassiana*, *Trichoderma* spp., and *Bacillus subtilis* under Integrated Pest Management (IPM) programs because of their safety to humans, beneficial organisms, and the environment.

**Status of banned and restricted pesticides in India**

According to the updated government notification dated 31.03.2024, several pesticides in India have been banned, withdrawn, refused registration, or restricted for use because of their adverse effects on human health, animals, and the environment. These regulatory actions were taken due to concerns such as toxicity, carcinogenicity, environmental persistence, bioaccumulation, and harmful effects on non-target organisms. The following tables present the current status of pesticides banned for manufacture, import and use, pesticides banned for domestic use but allowed for export manufacture, withdrawn pesticides, pesticides refused registration, and pesticides restricted for specific uses in India (CIB&RC, 2024).

**Table 1. Pesticides banned for manufacture, import and use**

| S. No. | Pesticide name | Chemical group | Ban/restriction date |
|---|---|---|---|
| 1 | Copper Acetoarsenite | Arsenical Compound | - |
| 2 | Benomyl | Benzimidazole Fungicide | 08.08.2018 |
| 3 | Paraquat Dimethyl Sulphate | Bipyridyl Herbicide | - |
| 4 | Aldicarb | Carbamate Insecticide | 17.07.2001 |
| 5 | Carbaryl | Carbamate Insecticide | 08.08.2018 |
| 6 | Methomyl | Carbamate Insecticide | 03.10.2023 |
| 7 | Alachlor | Chloroacetanilide Herbicide | 08.08.2018 |
| 8 | Pentachlorophenol | Chlorophenol Compound | - |
| 9 | Sodium Cyanide | Cyanide Compound | 08.08.2018 |
| 10 | Dinocap | Dinitrophenol Fungicide | 03.10.2023 |
| 11 | Nitrofen | Diphenyl Ether Herbicide | - |
| 12 | Ethylene Dibromide (EDB) | Fumigant | 17.07.2001 |
| 13 | Trichloro Acetic Acid (TCA) | Herbicide | 17.07.2001 |
| 14 | Calcium Cyanide | Inorganic Compound | - |
| 15 | Tridemorph | Morpholine Fungicide | 08.08.2018 |
| 16 | Sodium Methane Arsonate | Organoarsenical Herbicide | - |
| 17 | Chlorbenzilate | Organochlorine Acaricide | 17.07.2001 |
| 18 | Dicofol | Organochlorine Acaricide | 03.10.2023 |
| 19 | Tetradifon | Organochlorine Acaricide | - |

| S. No. | Pesticide name | Chemical group | Ban/restriction date |
|---|---|---|---|
| 20 | Pentachloro Nitrobenzene (PCNB) | Organochlorine Fungicide | 25.07.1989 |
| 21 | Aldrin | Organochlorine Insecticide | - |
| 22 | Benzene Hexachloride (BHC) | Organochlorine Insecticide | - |
| 23 | Chlordane | Organochlorine Insecticide | - |
| 24 | Dieldrin | Organochlorine Insecticide | 17.07.2001 |
| 25 | Endosulfan | Organochlorine Insecticide | 13.05.2011 / 10.01.2017* |
| 26 | Endrin | Organochlorine Insecticide | - |
| 27 | Heptachlor | Organochlorine Insecticide | - |
| 28 | Lindane (Gamma-HCH) | Organochlorine Insecticide | - |
| 29 | Toxaphene (Camphechlor) | Organochlorine Insecticide | 25.07.1989 |
| 30 | Dibromochloropropane (DBCP) | Organohalogen Fumigant | 25.07.1989 |
| 31 | Ethyl Mercury Chloride | Organomercury Compound | - |
| 32 | Methoxy Ethyl Mercury Chloride | Organomercury Compound | 08.08.2018 |
| 33 | Phenyl Mercury Acetate | Organomercury Fungicide | - |
| 34 | Chlorofenvinphos | Organophosphate Insecticide | - |
| 35 | Diazinon | Organophosphate Insecticide | 08.08.2018 |
| 36 | Dichlorovos | Organophosphate Insecticide | 08.08.2018 |
| 37 | Ethyl Parathion | Organophosphate Insecticide | - |
| 38 | Fenthion | Organophosphate Insecticide | 08.08.2018 |
| 39 | Menazon | Organophosphate Insecticide | - |
| 40 | Methyl Parathion | Organophosphate Insecticide | 08.08.2018 |
| 41 | Phorate | Organophosphate Insecticide | 08.08.2018 |
| 42 | Phosphamidon | Organophosphate Insecticide | 08.08.2018 |
| 43 | Thiometon | Organophosphate Insecticide | 08.08.2018 |
| 44 | Triazophos | Organophosphate Insecticide | 08.08.2018 |
| 45 | Trichlorfon | Organophosphate Insecticide | 08.08.2018 |
| 46 | Linuron | Phenylurea Herbicide | 08.08.2018 |
| 47 | Maleic Hydrazide | Plant Growth Regulator | 17.07.2001 |
| 48 | Fenarimol | Pyrimidine Fungicide | 08.08.2018 |
| 49 | Metoxuron | Urea Herbicide | - |

***:** (ad-interim order of the supreme court of India in the writ petition (civil) no. 213 of 2011 dated 13th may, 2011 and finally disposed of dated 10th January, 2017)

**Table 2. Pesticides banned for use but continued for manufacture for export**

| S. No. | Pesticide name | Chemical Group | Banned/withdrawal date |
|---|---|---|---|
| 1 | Captafol 80% Powder | Phthalimide Fungicide | 17 July 2001 |
| 2 | Dichlorvos | Organophosphate Insecticide | 20 March 2020 |
| 3 | Nicotin Sulfate | Botanical Insecticide | 11 May 1992 |
| 4 | Phorate | Organophosphate Insecticide | 20 March 2020 |
| 5 | Triazophos | Organophosphate Insecticide | 20 March 2020 |

**Table 3. Pesticides withdrawn in India**

| S. No. | Pesticide name | Chemical group | Withdrawal date |
|---|---|---|---|
| 1 | Dalapon | Herbicide | 15 June 2006 |
| 2 | Ferbam | Dithiocarbamate Fungicide | 15 June 2006 |
| 3 | Formothion | Organophosphate Insecticide | 15 June 2006 |
| 4 | Nickel Chloride | Inorganic Compound | 15 June 2006 |
| 5 | Paradichlorobenzene (PDCB) | Organochlorine Compound | 15 June 2006 |
| 6 | Simazine | Triazine Herbicide | 15 June 2006 |
| 7 | Sirmate | Fungicide | 24 September 2014 |
| 8 | Warfarin | Anticoagulant Rodenticide | 15 June 2006 |

**Table 4. Pesticides refused registration in India**

| S. No. | Pesticide name |
|---|---|
| 1 | 2,4,5-T |
| 2 | Ammonium Sulphamate |
| 3 | Azinphos Ethyl |
| 4 | Azinphos Methyl |
| 5 | Binapacryl |
| 6 | Calcium Arsenate |
| 7 | Carbophenothion |
| 8 | Chinomethionate (Morestan) |
| 9 | Dicrotophos |
| 10 | EPN |
| 11 | Fentin Acetate |
| 12 | Fentin Hydroxide |
| 13 | Lead Arsenate |
| 14 | Leptophos (Phosvel) |
| 15 | Mephosfolan |
| 16 | Mevinphos (Phosdrin) |
| 17 | Thiodemeton / Disulfoton |
| 18 | Vamidothion |

**Table 5. Pesticides restricted for use in India**

| S. No. | Pesticide name | Restriction details |
|---|---|---|
| 1 | Aluminium Phosphide | Use restricted to trained operators under government supervision |
| 2 | Captafol | Foliar spray banned; only seed treatment allowed |
| 3 | Carbofuran | Only 3% CG formulation permitted |
| 4 | Chlorpyriphos | Banned on Ber, Citrus and Tobacco |
| 5 | Cypermethrin | 3% Smoke Generator only through pest control operators |
| 6 | Dazomet | Not permitted on Tea |
| 7 | DDT | Restricted for public health vector control only |
| 8 | Dimethoate | Banned on fruits and vegetables consumed raw |
| 9 | Fenitrothion | Restricted except locust control and public health |

| S. No. | Pesticide name | Restriction details |
|---|---|---|
| 10 | Malathion | Restricted on several crops including tomato and mango |
| 11 | Mancozeb | Banned on Guava, Jowar and Tapioca |
| 12 | Methyl Bromide | Restricted to trained operators under supervision |
| 13 | Monocrotophos | Banned on vegetables; 36% SL phased out |
| 14 | Oxyfluorfen | Banned on Potato and Groundnut |
| 15 | Quinalphos | Banned on Jute, Cardamom and Sorghum |
| 16 | Trifluralin | Use allowed only in wheat with cautionary labeling |

## Agricultural impact of banned pesticides

### Positive impacts

### 1. Improved environmental safety

The ban on persistent and hazardous pesticides has reduced contamination of soil, groundwater, and agricultural produce. These restrictions have also helped protect biodiversity and minimize long-term ecological damage caused by toxic pesticide residues.

### 2. Promotion of bio-pesticides

Restrictions on toxic pesticides have encouraged the adoption of eco-friendly alternatives such as neem-based formulations, *Bacillus thuringiensis*, *Beauveria bassiana*, and *Trichoderma* spp. Bio-insecticides containing Azadirachtin are increasingly used in crops like cotton, rice, tomato, brinjal, cabbage, and tea for safer pest management.

### 3. Strengthening of integrated pest management (IPM)

The banning of hazardous pesticides has promoted Integrated Pest Management (IPM) practices involving biological control, cultural practices, resistant varieties, and need-based pesticide application. These approaches reduce excessive chemical use and help delay pesticide resistance in insect pests.

### 4. Reduction in health hazards

Highly toxic pesticides are associated with skin diseases, neurological disorders, respiratory complications, reproductive disorders, and cancer risks. Restrictions on hazardous pesticides help reduce occupational exposure among farmers and promote safer agricultural practices.

### Negative impacts

### 1. Limited availability of effective chemicals

Some banned pesticides were highly effective and inexpensive for controlling major pests. Farmers sometimes face difficulties in managing resistant pests after withdrawal of older molecules.

### 2. Increased cost of pest management

New-generation pesticides and bio-pesticides are generally costlier than conventional pesticides. This increases production costs for small and marginal farmers.

### 3. Pest resistance problems

Overdependence on limited approved pesticides may accelerate resistance development in pests such as whitefly, brown planthopper, bollworms, and aphids. Repeated use of the same pesticide groups reduces their long-term effectiveness.

### 4. Illegal use and black marketing

Despite restrictions, banned pesticides are sometimes illegally sold or used in rural areas because of lack of awareness and inadequate monitoring systems.

## Need for sustainable alternatives

India is gradually shifting toward sustainable pest management approaches because of increasing concerns regarding environmental pollution and food safety. Bio-pesticides and low-toxicity molecules such as Azadirachtin, *Bacillus thuringiensis*, *Beauveria bassiana*, and *Bacillus subtilis* are gaining importance as safer alternatives. Integrated Pest Management (IPM) strategies involving farmer training, pest surveillance, biological control, and judicious pesticide use should be strengthened for sustainable agricultural production.

## Conclusion

Pesticides are indispensable tools for modern agriculture; however, indiscriminate use of highly hazardous chemicals has created serious environmental and public health concerns. India has taken significant regulatory measures by banning and restricting several toxic pesticides under the Insecticides Act, 1968. These measures have positively contributed to environmental protection, safer food production, and promotion of sustainable agriculture.

Nevertheless, challenges such as pest resistance, higher cost of safer alternatives, and illegal pesticide use still exist. Therefore, balanced pest management strategies integrating chemical, biological, and cultural approaches are essential for sustainable agricultural development in India. Greater emphasis should be given to bio-pesticides, integrated pest management, farmer awareness, and strict regulatory enforcement to ensure long-term agricultural and environmental sustainability**.**

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ISSN : 2583-0910
**Agri-India TODAY**
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Peer reviewed
monthly newsletter

Article ID : 06/VI/32/0626

# FROM SMOKE TO GOLD: HOW THE SUPER SEEDER IS TURNING CROP RESIDUE INTO WEALTH

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## Abstract

Crop residue burning in North-West India has long been a pressing environmental and agricultural challenge, contributing to severe air pollution, greenhouse gas emissions, and soil degradation. Farmers, constrained by short sowing windows and high labour costs, often resort to burning rice stubble, which releases enormous amounts of carbon dioxide and particulate matter into the atmosphere. The Super Seeder, a tractor-mounted implement, offers a sustainable solution by simultaneously chopping residue, incorporating it into the soil, and sowing seeds in a single pass. This paper explores the Super Seeder's role in India's Viksit Bharat @2047 vision and balance use of inorganic fertilizer, comparing it with the Happy Seeder, analyzing its economic and ecological benefits, and highlighting real-world farmer experiences. Evidence shows that adoption of the Super Seeder reduces cultivation costs, increases wheat yield, improves soil fertility, and contributes to climate resilience. By addressing both environmental and economic concerns, the Super Seeder emerges as a most important technology for sustainable agriculture in India.

**Keywords:** Super Seeder; Crop residue management; Stubble burning; Sustainable agriculture; Soil health; Farmer income; Climate resilience; Viksit Bharat

## Introduction

Every October and November, North-West India experiences a choking haze caused by widespread stubble burning. Farmers, under pressure to sow the next wheat crop within 15–20 days of harvesting paddy, often resort to burning rice straw left behind by combine harvesters. This practice releases 141 MT of $CO_2$ annually and contributes significantly to particulate matter pollution, with $PM_{2.5}$ levels in Delhi rising up to 17 times higher than other sources during peak season[3]. Beyond air pollution, burning destroys soil carbon, microbial life, and water retention capacity, leading to declining productivity and rising input costs[4].

India's Viksit Bharat @2047 vision and balance use of the fertilizer emphasizes prosperity, sustainability, and self-reliance. Achieving these goals requires innovations that simultaneously improve farmer incomes and reduce environmental damage. The Super Seeder represents one such innovation, offering farmers a way to manage crop residue without burning, while enhancing soil fertility and profitability[1,2].

## Super Seeder Technology

The Super Seeder is a tractor-mounted implement designed to perform three critical tasks in a single pass: chopping rice straw, incorporating residue into the soil, and sowing seeds with fertiliser placement. Its rotavator blades, powered at ~210 rpm, chop standing rice straw into fine pieces, which are then mixed into the topsoil. Eleven-disc openers create furrows, while a dual-compartment hopper places seeds and fertiliser at precise depths. A trailing press wheel firms the seedbed, ensuring uniform germination [2,7].

This integrated approach saves farmers significant time and labour, eliminating the need for burning. By converting residue into organic matter instantly, the Super Seeder enhances soil fertility and reduces dependence on chemical fertilisers. Farmers benefit from faster field preparation, reduced fuel consumption, and improved crop establishment.

### Comparison with Happy Seeder

Another residue-management machine, the Happy Seeder, also prevents burning but uses a different approach. The Happy Seeder cuts straw and leaves it on the surface as mulch, which helps retain moisture, optimal temperature for wheat seed germination in heavy winter season and suppress weeds. In contrast, the Super Seeder incorporates residue into the soil, accelerating nutrient release and improving soil structure [6].

The choice between the two depends on soil type and farmer priorities. The Super Seeder is best suited for heavier soils and farmers seeking immediate yield gains, while the Happy Seeder benefits lighter soils where long-term moisture retention is critical. Although the Super Seeder requires a >60 HP tractor and higher fuel consumption, its rapid nutrient recycling and yield improvements make it attractive for farmers aiming to maximize productivity.

Figure 1. Super Seeder Sowing Process — From residue management to crop growth

### The Wealth Equation: Counting the Rupees

Economic trials reveal that the Super Seeder is not only environmentally beneficial but also financially rewarding. Compared to conventional tillage, farmers save ₹1,500–1,800 per acre in field preparation, reduce diesel use by 58.33%, and save 2–2.5 hours per acre. Seed use declines by 14%, fertiliser costs drop by 10.81%, and overall cultivation costs are reduced by 13.10%. Most importantly, wheat yield improves by 13.11%, resulting in a 36.15% increase in net profit (1,5).

## Conversion Paddy Straw Bales into Wealth

After harvesting paddy, farmers can use a baler to collect the loose straw left in the field and compress it into compact bales, and these bales become a valuable raw material for industries rather than being wasted through burning. The paper and packaging industry can process straw fibers into pulp, producing eco-friendly paper, cartons, and biodegradable packaging materials that reduce dependence on wood and plastics. With proper treatment, straw bales can also be converted into animal feed, providing fodder during lean seasons and supporting livestock productivity. In addition, straw can be processed into biochar and compost, which enriches soil organic carbon, improves fertility, and reduces reliance on chemical fertilisers. By linking farmers to these industrial and agricultural uses, paddy straw bales create a circular economy where residue is transformed into income, sustainable products, and healthier soils, turning what was once considered waste into a driver of rural wealth and environmental sustainability.

## Ecological Benefits

The Super Seeder's ecological benefits extend beyond immediate productivity gains. Incorporating residue into soil enhances organic carbon levels, contributing to carbon sequestration and climate change mitigation [4,8]. Organic matter improves water retention, reducing irrigation needs by one or two cycles per season. Farmers also report healthier soils with restored microbial life, which chemical fertilisers cannot replicate. Nutrients such as nitrogen, phosphorus, and potassium remain in the soil rather than being lost to the atmosphere, reducing fertiliser dependency and chemical runoff. By eliminating stubble burning, the Super Seeder also reduces $PM_{2.5}$ pollution, improving air quality for millions across North India. At scale, widespread adoption could significantly reduce the autumn smog that affects urban and rural populations alike (3).

## Case Studies

In Chunni Kalan, Punjab, five farmers acquired Super Seeders under a CSR-supported subsidy program. Within two years, stubble burning was eliminated across 621.5 acres, and machine owners earned ₹3,72,900 by hiring out their equipment. Farmers reported stronger, more resilient wheat crops, demonstrating both environmental and economic benefits[1].

In R.S. Pura, Jammu & Kashmir, wheat sown with the Super Seeder showed greater resilience to unseasonal rains and strong winds compared to conventionally planted crops. Local officials confirmed significantly less damage, highlighting the machine's role in building climate-resilient agriculture[7].

## Policy Support

Recognizing the high cost of machinery as a barrier, governments have introduced subsidies to encourage adoption. The Central Sector Scheme provides 50–80% subsidy on residue management machinery, while the E-Krishi Yantra Anudan Yojana offers 50% subsidy for small and marginal farmers [6]. In Jammu & Kashmir, farmers receive a 50% subsidy specifically for Super Seeder purchase [7]. These policies make advanced machinery accessible to smallholders, promoting widespread adoption and scaling of sustainable practices.

## Conclusion

The Super Seeder represents a transformative solution to India's stubble burning crisis. By combining environmental sustainability with economic profitability, it empowers farmers to achieve higher yields, lower costs, and healthier soils. Its adoption supports India's *Viksit Bharat @2047* vision, contributing to cleaner air, climate resilience, and rural prosperity. From ash to abundance, the Super Seeder demonstrates how technology can turn crop residue into wealth, offering both immediate and long-term dividends for farmers and society.

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ISSN : 2583-0910
**Agri-India TODAY**
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Peer reviewed
monthly newsletter

Article ID : 06/VI/33/0626

# SYNTHETIC APOMIXIS IN CROP PLANTS: A GENETIC STRATEGY FOR FIXATION OF HYBRID VIGOR AND SUSTAINABLE SEED SYSTEMS

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## Abstract

Synthetic apomixis is an advanced genetic strategy to fix hybrid vigor (heterosis) in crop plants through clonal seed production. In conventional hybrids, genetic segregation during sexual reproduction prevents stable inheritance of superior traits. Synthetic apomixis addresses this limitation by integrating apomeiosis, parthenogenesis, and endosperm development. The MiMe (Mitosis instead of Meiosis) approach enables the formation of unreduced gametes via targeted mutations in key meiotic genes. Parthenogenesis is induced by regulators such as BBM1, which trigger embryo development without fertilization. Recent progress in crops like rice has demonstrated high-frequency clonal seed formation with stable transmission of hybrid traits. However, challenges including endosperm imbalance, reduced fertility, and regulatory constraints remain for large-scale agricultural deployment.

**Keywords:** Synthetic apomixis; Heterosis; MiMe strategy; Clonal seeds

## Introduction

Heterosis, or hybrid vigor, is a fundamental biological phenomenon wherein hybrid offspring exhibit phenotypic superiority over their inbred parents in traits such as biomass, growth rate, and stress adaptability. This phenomenon has been central to global agricultural productivity for over a century. However, the primary limitation of hybrid crop production is the segregation of genotypes and phenotypes during sexual reproduction, which prevents the maintenance of these elite qualities in subsequent generations. Consequently, agricultural systems are locked into laborious and costly cycles of annual hybrid seed production. Apomixis, a natural process of asexual reproduction through seeds, presents a theoretical solution by enabling the inheritance of the maternal genome without fertilization or genetic recombination. Because naturally apomictic traits are absent in major staple crops, and introgression from wild relatives has achieved limited success, molecular engineering has introduced synthetic apomixis a method designed to artificially assemble the components of apomictic propagation to permanently fix hybrid vigor.

## The Biological Architecture of Natural Apomixis

In nature, apomixis occurs in two basic forms: sporophytic and gametophytic. Sporophytic apomixis involves the direct development of embryos from somatic cells of the ovule, often occurring concurrently with sexual reproduction, as seen in Citrus species. Gametophytic apomixis is characterized by the derivation of embryos from an unreduced embryo sac. This can occur via diplospory (where the embryo sac develops from a megaspore mother cell with suppressed meiosis) or apospory (where it originates from a somatic cell). A central challenge in agricultural biotechnology is mimicking these unreduced, clonal pathways in sexually reproducing crops.

## Molecular Engineering of Synthetic Apomixis

The engineering of synthetic apomixis requires the precise molecular coordination of three critical reproductive steps: apomeiosis (the formation of unreduced female gametophytes), parthenogenesis or genome elimination (embryo development without a paternal genomic contribution), and the formation of a viable endosperm.

### Apomeiosis via the MiMe Strategy

To bypass meiosis and prevent genetic recombination, researchers frequently employ the Mitosis instead of Meiosis (MiMe) strategy. MiMe requires the disruption of three specific events:

- Inhibition of double-strand breaks (DSBs): Genes such as SPO11-1 or PRD1 are disabled to prevent chromosomal pairing and recombination.
- Premature separation of sister chromatids: Subunits like REC8 are mutated to alter kinetochore orientation and chromatid cohesion during the first meiotic division.
- Skipping the second meiotic division: Mutations in cell cycle regulators, such as OSD1, prevent the secondary division that typically halves the chromosome number. Together, these modifications convert meiosis into a mitotic-like division, yielding clonal diploid gametes that retain the exact genetic code of the parent.

### Embryogenesis

Genome Elimination and Parthenogenesis Once an unreduced egg cell is formed, it must develop into an embryo without true fertilization. Two primary methodologies are utilized:

**Genome Elimination:** This approach allows for fertilization but subsequently induces the degradation of the paternal chromosomes. This can be achieved by manipulating centromere-specific histones (e.g., CENH3 variants) or by inducing mutations in pollen-specific genes like MATRILINEAL (MTL), which trigger reactive oxygen species bursts and chromosome fragmentation in pollen.

**Parthenogenesis:** A more highly successful method involves the ectopic expression of specific trigger genes that artificially initiate embryo development from an unfertilized egg. Genes such as BABY BOOM (BBM1)—an AP2/ERF transcription factor—and PsASGR-BBML have demonstrated significant efficacy in inducing parthenogenesis in cereal crops like rice and maize.

### Endosperm Formation

The endosperm is a nutrient-rich tissue vital for seed viability. While autonomous endosperm development (occurring without fertilization) is observed in some natural apomicts, its molecular induction in crops is highly complex, often involving the manipulation of the FIS-PRC2 chromatin-modifying complex or auxin biosynthesis genes (e.g., OsYUC11). Currently, most synthetic apomixis systems rely on pseudogamy, wherein normal fertilization of the central cell is permitted solely to trigger endosperm growth, while the cloned embryo develops parthenogenetically alongside it.

### Recent Empirical Advancements

The transition of synthetic apomixis from theory to empirical reality has seen its most profound successes in rice (Oryza sativa). By combining the MiMe triple mutation (pair1/rec8/osd1) with the egg-cell-specific expression of the OsBBM1 parthenogenesis gene, researchers have successfully produced clonal diploid seeds at frequencies exceeding 95% in hybrid rice. Crucially, these synthetic apomicts exhibited seed-setting rates comparable to wild-type plants, and the elite hybrid vigor was stably transmitted across multiple generations with no observable phenotypic penalties.

### Agricultural Implications and Future Challenges

The commercial realization of synthetic apomixis represents a paradigm shift for plant breeding. It promises the permanent fixation of heterosis, increased breeding efficiency by removing the need for continual parental line crossing, and the democratization of elite seeds for farmers in developing regions by lowering recurring input costs.

However, substantial biological and regulatory hurdles remain. Endosperm imbalance is a persistent issue, as conflicts between parthenogenetic embryo formation and central cell fertilization frequently lead to seed abortion. Furthermore, haploid induction methods relying on genome elimination suffer from drastically reduced plant fertility. Finally, as this technology is fundamentally dependent on advanced CRISPR/Cas9 genome editing, its deployment will necessitate navigating complex and variable global regulatory frameworks before entering the commercial agricultural market.

## Conclusion

Synthetic apomixis effectively bridges the gap between classical hybrid breeding and modern molecular genetics. By resolving the inherent genetic instability of hybrid crops, the continued refinement of apomeiosis, parthenogenesis, and endosperm regulatory networks paves the way toward a more resilient, uniform, and efficient global agricultural system.

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ISSN : 2583-0910
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Peer reviewed
monthly newsletter

Article ID : 06/VI/34/0626

# GREEN LEDGER FARMING: LINKING CARBON REDUCTION WITH FARM INCOME

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## Abstract

Indian agriculture must balance food security with the urgent need to mitigate greenhouse gas emissions. This article introduces the "Green Ledger" framework, an integrated approach that combines quantitative emission tracking with farm profitability analysis. By assessing major gases like $CO_2$, $CH_4$ and $N_2O$ alongside emerging drivers such as Black Carbon, it identifies key environmental liabilities and their mitigation pathways. The study evaluates various measurement technologies and demonstrates that climate-smart practices, such as precision fertilization and agroforestry, enhance resource-use efficiency and net returns. Ultimately, this framework transforms emission reduction from a regulatory burden into a profitable opportunity, supported by emerging revenue streams like carbon credits, ensuring a sustainable future for Indian agroecosystems.

**Keywords:** Carbon Credits, Climate-Smart Agriculture, Farm Profitability, GHG Mitigation and Green Ledger.

## Introduction

Agriculture in India stands at a critical crossroads. While agroecosystems are the bedrock of food security and rural livelihoods, they are also significant contributors to anthropogenic greenhouse gas (GHG) emissions. However, unlike industrial sectors, agriculture possesses a unique dual capacity in that it acts as both a source of emissions and a potential carbon sink. To navigate this complexity, we must adopt a "Green Ledger" approach. This involves moving beyond simple yield metrics to a more holistic accounting system. Such a system integrates the quantitative tracking of gases like Carbon Dioxide ($CO_2$), Methane ($CH_4$) and Nitrous Oxide ($N_2O$) with rigorous economic evaluation. For the Indian farmer, a mitigation strategy is only as viable as its impact on the bottom line. By balancing the environmental ledger with the economic one, we can chart a course toward truly sustainable and climate-resilient agriculture.

## The "Big Three" GHGs: Understanding the Emissions Portfolio

Before managing the ledger, we must identify the primary liabilities. In Indian agroecosystems, three major gases dominate the climate profile. Understanding their Global Warming Potential (GWP) and their specific agricultural drivers is the first step toward mitigation.

**Table 1: Primary Agricultural Greenhouse Gases**

| Greenhouse Gas | Global Warming Potential (100-yr Horizon) | Primary Agricultural Source | Mitigation Strategy |
|---|---|---|---|
| **Carbon Dioxide ($CO_2$)** | 1 (Base Reference) | Tillage, diesel machinery, residue burning | Agroforestry and no-till farming |

| Greenhouse Gas | Global Warming Potential (100-yr Horizon) | Primary Agricultural Source | Mitigation Strategy |
|---|---|---|---|
| **Methane ($CH_4$)** | 27–30 | Flooded rice paddies, enteric fermentation | AWD, SRI and improved feed |
| **Nitrous Oxide ($N_2O$)** | 273 | Inefficient nitrogen fertilizer use | LCC and Neem-coated urea |

**Source:** IPCC (2021).

**Table 2: Emerging and Indirect Climate Drivers**

| Gas/Pollutant | Impact Level (GWP 100-yr Horizon) | Primary Agricultural Source | Mitigation Strategy |
|---|---|---|---|
| **Black Carbon (Soot)** | Very High (460–1,500) | Open-field stubble burning | In-situ residue management |
| **Ammonia ($NH_3$)** | Indirect Warming | Urea volatilization from soil | Deep placement of fertilizers |
| **HFCs (Refrigerants)** | Extreme (124–14,800) | Cold storage and transport leaks | Natural refrigerant technology |

**Source:** CCAC (2022).

### Methods for Quantitative Assessment: Balancing the Books

Accurate quantification is the backbone of the Green Ledger. In the diverse landscape of Indian farming, different methods offer varying levels of precision and cost-effectiveness.

1. **Closed Chamber Method:** This is the most accessible field level accounting tool. By capturing gas flux from the soil surface, researchers can precisely measure how specific management practices change emission rates.
2. **Eddy Covariance Technique:** This is a high precision approach using sensors to measure the continuous breath of the ecosystem. While technically demanding, it provides accurate data for landscape level carbon accounting.
3. **Digital Estimation Models:** Tools like the *Cool Farm Tool* allow for virtual accounting. By inputting local soil data and management history, these models can predict emissions at a fraction of the cost of physical sampling.
4. **Remote Sensing and AI:** This represents the modern frontier. Satellite based monitoring of methane plumes and biomass changes allow for real time regional scale environmental auditing.

### The Economic Pivot: Can "Green" be Profitable?

The most persistent myth in sustainable agriculture is that low carbon means low profit. In reality, many GHG mitigation strategies are rooted in Resource Use Efficiency (RUE). By reducing the waste of expensive inputs like water, fertilizer and fuel, farmers naturally lower their emissions while increasing their margins.

**Table 3: Economic Feasibility and Abatement Potential of Climate-Smart Practices**

| Mitigation Practice | Impact on Cost of Cultivation | Impact on Net Returns | Benefit-Cost Ratio (BCR) |
|---|---|---|---|
| Precision Fertilization | Decrease through lower input waste | Increase via optimized yield | High |

| **Mitigation Practice** | **Impact on Cost of Cultivation** | **Impact on Net Returns** | **Benefit-Cost Ratio (BCR)** |
|---|---|---|---|
| Conservation Tillage | Decrease through less fuel and labor | Stable to Increase | Moderate-High |
| Agroforestry | Increase due to initial setup cost | High via multi-crop income | High in the long term |
| AWD in Rice | Decrease through lower pumping costs | Stable | High |

**Source:** Krizkova, A. (2022).

### Factors Influencing the Emission Ledger

The Green Ledger varies significantly across India's diverse agro-climatic zones. Key variables include:

- **Soil Texture and Health:** Heavy soils may trap more carbon but require careful moisture management to avoid $N_2O$ spikes.
- **Irrigation Intensity:** Shifting from traditional flood irrigation to micro-irrigation is perhaps the single most effective way to decarbonize the water-energy-food nexus.
- **Cropping Diversification:** Moving away from monocultures to legume inclusive rotations reduces the need for synthetic nitrogen and directly lowers the $N_2O$ liability.

### The Role of Carbon Credits: A New Revenue Stream

A critical component of the Green Ledger is the opportunity for farmers to be compensated for their environmental services. Through Voluntary Carbon Markets, Indian farmers who adopt verified sequestering practices can generate carbon credits. These credits act as a secondary cash crop that provides financial resilience against climate induced crop failures.

### Conclusion

The future of Indian agriculture lies in the successful integration of environmental health and economic wealth. By adopting a Green Ledger framework, we move away from viewing GHG mitigation as a regulatory burden and start seeing it as an efficiency driven opportunity. Quantitative assessment provides the data and economic evaluation provides the motivation. Together, they form a robust strategy for a climate resilient, sustainable and profitable agricultural future for India. The Green Ledger approach shows that sustainability and profitabilityare no longer competing goals. They can grow together toward a resilient agricultural future.

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ISSN : 2583-0910
Agri-India TODAY
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Peer reviewed
monthly newsletter

Article ID : 06/VI/35/0626

# WOOD CELLULOSE AS A RAW MATERIAL FOR RAYON AND OTHER FIBERS & INNOVATIONS IN COMPOSITE WOOD PRODUCTS

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## Introduction

Wood is one of the most versatile natural resources, offering applications that extend far beyond traditional timber uses. Among its most significant components is cellulose, a fundamental structural material that serves as the basis for numerous industrial products. Cellulose extracted from wood has become a critical raw material for the production of rayon and other regenerated fibers. Simultaneously, technological advancements have driven innovations in composite wood products such as plywood, particle board, and medium-density fiber board (MDF). These developments highlight the expanding role of wood in modern industries, emphasising sustainability, efficiency, and value addition. Wood Cellulose and Fiber Production Cellulose is the primary structural constituent of plant cell walls and represents a renewable, biodegradable, and abundant biopolymer. In the wood processing industry, cellulose is extracted through chemical pulping processes. This purified cellulose serves as the foundation for regenerated fibers such as rayon. Rayon production involves dissolving cellulose and reforming it into fine filaments, producing fibers that combine natural origin with desirable textile properties. These fibers are widely valued for their softness, breathability, and versatility, making them suitable for clothing, medical textiles, and industrial uses.

Advantages of Cellulose-Based Fibers Cellulose-derived fibers offer several environmental and functional advantages. Being sourced from renewable raw materials, they reduce dependency on petroleum-based synthetic fibers. Additionally, such fibers are biodegradable and exhibit favourable moisture absorption properties. Their production supports sustainable material cycles and aligns with growing demand for eco-friendly textile alternatives.

Innovations in Composite Wood Products Composite wood products represent a major advancement in wood utilization technology. These products are manufactured by combining wood elements such as veneers, particles, or fibers with adhesives under controlled pressure and temperature. Plywood, particle board, and MDF exemplify engineered solutions designed to maximise raw material efficiency, improve dimensional stability, and enhance mechanical performance. Such products enable the use of smaller logs, residues, and wood waste, thereby supporting sustainable forest resource management.

## Benefits of Composite Wood Products

Engineered wood products provide numerous benefits including efficient raw material usage, uniform quality, reduced cost, and design flexibility. They also contribute to sustainability by utilising wood residues and minimising waste. Improved strength-to-weight ratios and dimensional stability further enhance their suitability for furniture, construction, and interior applications.

## Conclusion

The utilisation of wood cellulose for regenerated fibers such as rayon demonstrates the expanding industrial significance of forest resources. At the same time, innovations in composite wood products illustrate how technological progress can enhance efficiency, sustainability, and economic value. Together, these developments underscore the importance of scientific management, sustainable resource utilisation, and continuous innovation in the forest-based sector.

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ISSN : 2583-0910
Agri-India TODAY
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Peer reviewed
monthly newsletter

Article ID : 06/VI/36/0626

# USE OF ZEBRAFISH IN RESEARCH

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## Introduction

Wild-type (WT) zebrafish are widely used in biomedical research as a foundational model for developmental biology, genetics, disease modeling, and drug discovery. Zebrafish (*Danio rerio*) have become a versatile model in precision medicine, bridging fundamental biology with translational applications. Their rapid development, transparent embryos, and 70% genetic homology to humans allow for real-time observation of organogenesis, tissue regeneration, and modeling of human disease. Human biology is inherently complex, making direct experimentation and observation both challenging and, in many cases, ethically unfeasible. To overcome these challenges, scientists use model organisms-species that are extensively studied due to a thorough understanding of their genetics, physiology, and development. These organisms serve as simplified systems to investigate complex biological processes in a more manageable and ethically acceptable way.

## Scientific classification

| | |
|---|---|
| Kingdom: | Animalia |
| Phylum: | Chordata |
| Class: | Actinopterygii |
| Order: | Cypriniformes |
| Family: | Danionidae |
| Subfamily: | Danioninae |
| Genus: | Danio |
| Species: | D. rerio |

## Uses of Wild-Type Zebrafish in Research

**Developmental Biology:** Due to their external fertilization and transparent embryos, researchers can observe the organ formation, cell migration, and neurodevelopment under a microscope in real-time.

**Disease Modeling:** WT zebrafish are used for base disease models including tumor progression, neurological disorders, and cardiovascular conditions by introducing human cancer cells (xenografts) or using drug-induced diseases.

**Drug Discovery & Toxicology:** Their high fecundity (large numbers of offspring) allows for high-throughput screening of drug candidates, checking for toxicity and therapeutic efficacy at cellular and organism levels.

## Why Wild-Type Zebrafish are Preferred for Research

**Transparency**: Larvae allow imaging of live cells and organs without invasive procedures.

**Fast Development**: Key organs form within 48 hours post-fertilization.

**High Fecundity**: Females produce hundreds of eggs per week, allowing for large-scale, cost-effective studies.

**High Genetic Homology**: Roughly 70% of human genes have a zebrafish orthologue

## Why use zebrafish to study human disease?

While mice and rats was the choices for modeling human diseases in the past years, nowadays the use of wildtype zebrafish is rapidly gaining popularity for modelling human disease. Zebrafish are tropical fresh-water fish in the minnow family. In the wild, they are found in rivers and ponds of India, however they are now often available in pet shops.

The name “zebrafish” comes from the horizontal blue stripes on each side of their bodies. In fact, 70% of human genes are found in zebrafish. Another advantage is that adult zebrafish breed readily (approximately every 10 days) and can produce as many as 50 to 300 eggs at a time. This is quite different from mice as they generally produce litters of one to 10 pups and can only bear approximately three litters in their lifetime. Scientific experiments are generally repeated multiple times in order to prove that the results are accurate, so having an animal that can produce a large number of offspring over and over is helpful.

## Advantages

- Zebrafish offer unique advantages for studying human diseases and exploring potential therapies. Key features include external fertilization, rapid development, high fecundity, ease of genetic manipulation, and suitability for real-time imaging and chemical screening.
- Zebrafish reach sexual maturity in 3–4 months and can produce hundreds of embryos weekly. Their high fecundity and low maintenance costs make them ideal for large-scale pharmacological and genetic studies.
- One of the most distinctive advantages of the zebrafish model is the optical transparency of its embryos and larvae, allowing a real-time imaging of cellular dynamics and organ development. This feature is particularly important in the context of developmental biology and high-resolution microscopy, making the scientists able to observe dynamic process in real time in live organisms. Moreover, in addition to the external fertilization and rapid embryogenic development, the major organs systems are formed within 24–72 h post fertilization, making zebrafish a great time-efficient system to investigate the vertebrate embryology

## Conclusion

The timing of the adoption of zebrafish as an emerging model organism could not be better, as mouse studies often fail to translate to humans. Although no animal can perfectly model a human disease, I believe these little striped swimmers have great potential for advancing medical research in the future.

ISSN : 2583-0910
**Agri-India TODAY**
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Peer reviewed
monthly newsletter

Article ID : 06/VI/37/0626

# BREAKING DEPENDENCE: INDIA'S FERTILIZER VULNERABILITY AND THE CASE FOR REGENERATIVE AGRICULTURE ALIGNED WITH SDG 2, 12, 13 AND MISSION LIFE FOR VIKSIT BHARAT 2047

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## Abstract

Geopolitical tensions around the Strait of Hormuz exposed critical vulnerability in India's agricultural system: extreme import dependence for fertilizers. When phosphate supplies tightened, fertilizer costs surged beyond affordability for 160 million smallholder farmers. Rather than temporary disruption, this signals structural weakness demanding systemic transformation. This paper examines geopolitical-agricultural linkages and presents evidence-grounded strategies for transitioning toward regenerative agriculture aligned with SDG 2, 12, 13 and Mission LiFE. Through state-level analysis (Punjab ZBNF initiatives and Uttar Pradesh FPOs), we demonstrate feasible pathways to reduce synthetic fertilizer dependency 40-50% within five years while maintaining yield stability. Success requires deliberate policy incentives, explicit barrier acknowledgment (subsidy reduction resistance, yield risks, extension capacity gaps), and realistic implementation timelines. This work bridges geopolitical risk analysis and agricultural policy reform, addressing literature gaps while identifying both opportunities and implementation challenges for India's 2047 sustainable development vision.

**Keywords**: Fertilizer vulnerability; Geopolitical risk; Regenerative agriculture; SDGs; Implementation barriers; Farmer resilience

## Introduction: Structural Fragility in Agricultural Supply Chains

India feeds 18% of humanity through agricultural output from 2.4% of global arable land a paradoxical achievement resting on precarious foundations. With 160 million farming households and agriculture contributing 18% of GDP, the sector anchors rural livelihoods and national food security. Yet this productivity depends critically on imported fertilizers: approximately 35-40% of total consumption, with phosphate imports satisfying 60% of demand and potassium dependency exceeding 90%. This import reliance was manageable when supply chains remained stable. That assumption collapsed dramatically. Geopolitical tensions around the Strait of Hormuz through which 21% of global maritime trade passes—disrupted fertilizer supplies. Iran, historically exporting 3 million tonnes of phosphate annually (7-8% of global output), faced sanctions constraining exports. Global phosphate spot prices surged from $250-280/tonne (2021) to $650-720/tonne (2023); potassium exceeded $1,000/tonne versus pre-crisis $350-400. For India, this created fiscal and economic crisis. Government subsidy burden escalated from ₹80,000 crore to ₹95,000 crore annually, straining fiscal capacity. In Punjab producing 50% of national wheat and rice fertilizer consumed 55% of production expenses by 2023 versus 35% two years prior. Uttar Pradesh farmers reduced nitrogen application 20-30% to manage costs, risking yield penalties. This crisis exposed not temporary supply disruption but structural vulnerability. It simultaneously presents opportunity for transformative change toward regenerative agriculture aligned with SDG targets and Mission LiFE philosophy.

**Geopolitical Vulnerability and the Case for Demand-Side Transformation** Global fertilizer markets suffer from dangerous concentration. Approximately 40% of phosphate supplies originate from three sources: Morocco, China, and historically Iran. Domestic phosphate production (₹4,500-5,500/tonne) costs more than imports (₹2,800-3,200/tonne pre-crisis), making import dependence economically rational. However, this strategy overlooked geopolitical risk. When Iranian exports restricted, alternative sources faced limitations: Morocco's Atlantic supplies vulnerable to weather; Chinese supplies compete with rising Asian demand. The Hormuz disruption increased shipping insurance 300-400%, extended transit times 3-4 weeks, and pushed landed costs 30-40% higher. Government subsidy expansion provided short-term relief but generated moral hazard: farmers applied excess fertilizer assuming continued price protection, deepening long-term sustainability problems. Forward-looking risks intensify: climate change threatens North African phosphate deposits through water scarcity; geopolitical fragmentation will worsen. India cannot achieve supply-side food security through import substitution domestic production will never reach demand. The only sustainable solution demands demand-side transformation: consuming less synthetic nitrogen through biological fixation, optimizing nutrient use through precision agriculture, and rebuilding soil organic matter as nutrient reservoirs. This is pragmatic risk mitigation, not environmental romanticism.

## SDG Alignment and Evidence from the Ground: Punjab and Uttar Pradesh

India's SDG commitments intersect directly with agricultural transformation. SDG 2 demands nutritional security through sustainable food systems yet Indian agriculture produces abundant calories while generating micronutrient deficiencies (52% women and 30% children anemic despite food availability). SDG 12 requires reducing chemical pollutant releases; Indian agriculture contaminates groundwater with nitrogen runoff (Punjab/Haryana aquifers exceed WHO safe nitrate limits) and pesticide residues. SDG 13 addresses agriculture's 13% contribution to national emissions. Mission LiFE reframes sustainability from constraint to livelihood opportunity. However, SDG language often obscures implementation realities. Meeting SDG 2 while accommodating growing food demand on diminishing land requires productivity increases. Viksit Bharat 2047 envisions developed India with rising consumption. Agriculture must simultaneously support development and remain sustainable. This tension demands pragmatic, sequenced solutions rather than rhetorical commitments.

Evidence from field experiences clarifies feasibility. Punjab's Zero Budget Natural Farming (ZBNF) program (since 2019) trained 5,000-7,000 farmers. Initial yield reductions of 15-25% occurred over two seasons, then gradually stabilized for those integrating complementary practices (crop residue management, mulching, legume intercropping). Critical insight: farmers abandoning ZBNF lacked premium markets; those capturing organic/low-chemical price premiums sustained engagement. Subsidy expansion alone failed economic incentives proved decisive. Uttar Pradesh's 850+ Farmer Producer Organizations (FPOs) achieved 30-40% cost reductions for bio-fertilizer bulk procurement.

FPOs with embedded technical support maintained 75-85% member retention versus 35-40% without. Adoption patterns revealed: 15-20% were values-driven; 80-85% pragmatically economics-driven. These lessons demonstrate that transformation is achievable but 'not automatic' conditional on price incentives, institutional support, and realistic timelines. Five-year targets for 40-50% dependency reduction are realistic only if policy reflects farm-level realities.

### Strategic Pathways and Implementation Barriers

Four integrated strategies emerge from evidence: (1) Biological nutrient management nitrogen-fixing bacteria, phosphate-solubilizing organisms, and mycorrhizal fungi satisfy 30-50% of nutrient demands; combined with precision agriculture (soil testing, GPS application), achieves 25-35% fertilizer reduction; (2) Legume integration pulses and oilseeds fix atmospheric nitrogen, reducing nitrogen requirements in subsequent crops 20-30 kg/hectare, improving soil health and farmer income through diversification; (3) Organic waste valorization composting units, vermicompost centers, and biogas facilities recover nutrients and energy while generating employment; (4) Farmer-producer organizations collective input procurement reduces costs 30-40%, improves bargaining power, and enables implementation at scale. Soil testing currently reaches <15% of farmers nationally, establishing baseline gaps for precision agriculture expansion.

Yet significant implementation barriers threaten scaling: (1) Fiscal constraints subsidy reduction faces political resistance while competing with other demands; (2) Yield risks transition periods threaten marginal farmer livelihoods and require income bridges and crop insurance; (3) Extension capacity gaps India maintains approximately 1 extension worker per 2,000 farmers with inadequate sustainable agriculture training; (4) Market infrastructure deficiency certification costs remain high, premium price markets are thin and concentrated in urban areas, and smallholder access is limited; (5) Structural constraints land fragmentation (average <1 hectare nationally) creates economies-of-scale challenges. Solutions exist for each barrier, but require integrated policy design and political commitment sustained across electoral cycles, currently uncommon in Indian governance.

### Conclusion: Crisis as Inflection Point

The fertilizer crisis represents a genuine inflection point for Indian agriculture. Rather than treating this as temporary shock managed through subsidy expansion, enlightened policy should leverage crisis-induced flexibility for transformative change. Evidence from Punjab and Uttar Pradesh demonstrates that sustainable adoption accelerates when driven by economic incentives and institutional support, not moral appeals. Yield maintenance during transition remains non-negotiable. Transition subsidies and premium price assurance prove more effective than extension messaging alone. Transformation is achievable but requires specific conditions: sustained budget reallocation (25-30% of agricultural expenditure toward sustainable initiatives by 2030), genuine extension system strengthening, farmer participation in policy design, and realistic institutional development timelines. These preconditions are not assured.

Yet alternatives offer no respite. Continued import dependence amid intensifying geopolitical fragmentation exposes India to periodic crises and eroding farmer incomes. The choice between difficult reform now and crisis management repeatedly is not actually a choice but economic inevitability. The question is timing. Reducing synthetic fertilizer dependency 40-50% while maintaining productivity strengthens food security, improves soil health and micronutrient density, addresses malnutrition, reduces groundwater contamination, enhances farmer resilience against supply shocks, fulfills SDG commitments, and realizes Mission LiFE's vision of conscious environmental stewardship integrated with livelihood security. Acting now, leveraging this moment of policy flexibility, offers the best prospect for transforming Indian agriculture toward sustainability, resilience, and genuine prosperity for farming communities across the journey toward Viksit Bharat 2047.

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ISSN : 2583-0910
Agri-India TODAY
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Peer reviewed
monthly newsletter

Article ID : 06/VI/38/0626

# BIOGAS TECHNOLOGY: A PATHWAY TO SUSTAINABLE ENERGY AND A CIRCULAR ECONOMY

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## Introduction

Biogas is a sustainable and environmentally friendly alternative to fossil fuels for rural energy needs. Biogas, a renewable energy source produced by anaerobic digestion of organic materials, reduces greenhouse gas emissions and manages waste. The digested slurry, a byproduct, improves soil fertility when applied. Anaerobic breakdown of organic materials in a sealed digester produces biogas, with the help of microorganisms. Feedstock includes cattle dung, agricultural residues, municipal and industrial waste, food waste, and wastewater sludge. Biogas has a calorific value of 4500-5500 kcal/m$^3$ and consists of methane (40–65%) and carbon dioxide (30–40%), with trace amounts of other gases. A biogas application in rural households can be for cooking, heating, lighting & generating power. 1 m$^3$ of biogas from a biogas plant is sufficient for cooking for 3-4 people. Biogas can be used in a diesel-biogas engine to generate energy in off-grid settings. Electricity powers household lighting, irrigation, dairy, and other agricultural needs. The biogas requirement depends on the application. The daily cooking biogas requirement is about 0.24 m$^3$ per person. The lighting needs about 0.13 m$^3$ of biogas per person per day. Engine operation needs about 0.5 m$^3$ of biogas per hour per horsepower (hp) of engine capacity.

Digested slurry, a biogas byproduct, makes good organic fertilizer. It blends well with soil and conditions it, enhancing texture, moisture retention, and microbial activity. Digested slurry strengthens plants against pests and diseases. It reduces farmers' reliance on chemical fertilizers, making farming more sustainable and increasing crop yields. Compared to farmyard manure, digested slurry has more nutrients. In contrast to farm yard manure, which has 0.5–1.0% N, 0.5–0.8% P, and 0.5–0.8% K, the digested slurry has 1.5–2.0% N, 1.0% P, and 1.0% K.

## Powering a sustainable future

Biogas is a clean, renewable, and sustainable source of energy that can power small farms and rural households by converting cattle dung and other biodegradable waste into useful energy. It provides solutions to energy and waste management problems and improves agricultural productivity by using digested slurry as an organic fertilizer and soil conditioner. In many poor countries, especially in rural and peri-urban areas, electricity and clean cooking fuels are scarce. Biogas technology reduces family energy expenses and enhances energy security by replacing firewood and LPG. Biogas plants also help the scientific disposal of organic waste, minimizing pollution, increasing sanitation, and safeguarding the environment. Biogas cooking also reduces indoor air pollution from biomass fuels and enhances air quality and living conditions. Biogas systems prevent contamination of surface and groundwater by animal feces, reducing odor emissions and safeguarding water resources.

## Designs that Powers Sustainability

The most popular biogas designs are the KVIC (Khadi and Village Industries Commission) and the Deenbandhu biogas plant. The KVIC biogas plant is one of the oldest and most widely used floating-drum biogas models developed in India for rural energy generation. It is characterized by its simple design, high gas-generation efficiency, and suitability for modest household and community-level applications. The fixed dome Deenbandhu biogas plant is a low-cost alternative to KVIC biogas plants in India. This plant reduces construction and maintenance costs while also increasing the thermal efficiency and durability.

## Biogas-based circular economy for rural areas

Biogas technology is the best example of the circular economy. Using biogas-based circular economy models in rural regions can improve energy and waste management. Anaerobic digestion can transform agricultural wastes and livestock waste into biogas, improving energy independence and reducing greenhouse gas emissions in rural regions. Biogas generation from animal waste and agricultural waste seems promising in rural India, with small-scale plants (2-20 m³) meeting local energy needs. Biogas can reduce reliance on traditional fuels, conserving energy and firewood. Biogas plant digested slurry is a good agricultural fertilizer since it contains nitrogen (Fig. 1).

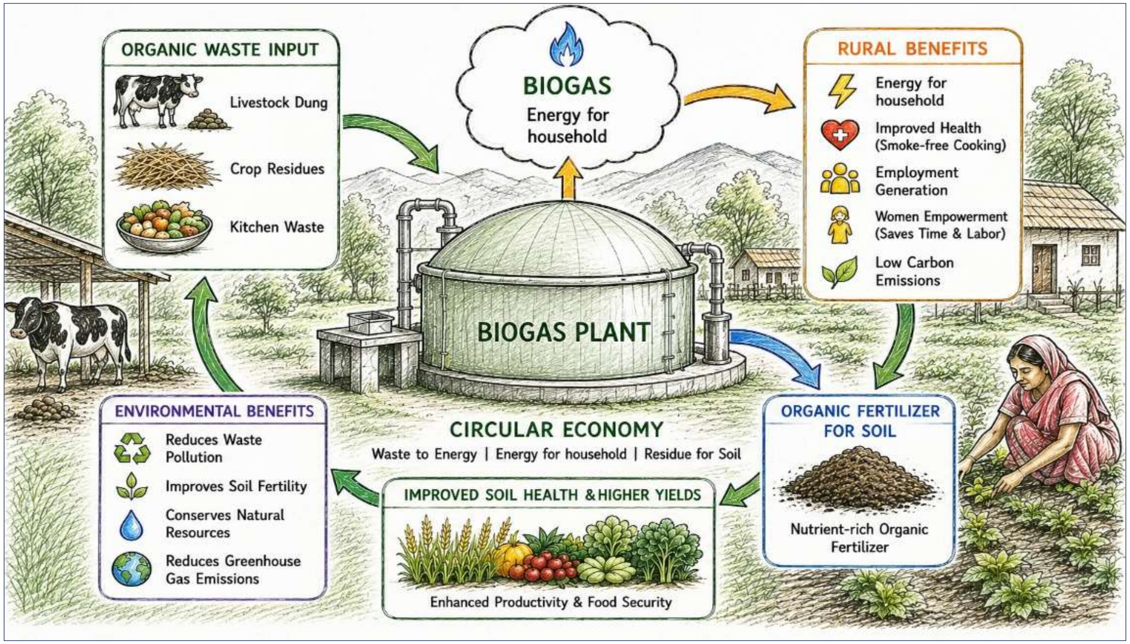

**Fig. 1: Biogas based circular economy**

## Schemes Driving Biogas Adoption

The central nodal agency, the Ministry of New and Renewable Energy (MNRE), promotes biogas technology and assists in its construction. MNRE's Central Financial Assistance (CFA) is critical to various components of the biogas effort, including.

| Scheme | Main Focus | Beneficiaries |
|---|---|---|
| Biogas Programme | Small & medium biogas plants | Rural households, dairy farmers |
| GOBARdhan | Waste-to-wealth & sanitation | Villages, Panchayats |
| SATAT | Compressed Bio-Gas for transport | Entrepreneurs & industries |

### Biogas programme

CFA for small biogas plants (1-25 $m^3$/day plant capacity) is Rs. 9800/- to Rs. 70,400/- per plant based on the size of the plant. For power generation and thermal application (25 – 2500 $m^3$/day plant capacity): Rs. 35,000/- to Rs. 45,000/kW power generation and Rs. 17,500 /- to Rs. 22,500/kW equivalent for thermal applications (25 – 2500 cubic meter/day plant capacity) (The eligible CFA would be 20% higher than Standard CFA in for NER, Island, Registered Gaushalas and SC/ST beneficiaries).

### GOBARdhan

The GOBARdhan scheme was launched by the national government in 2018 to convert cattle dung and organic waste into biogas, bio-CNG, and organic manure. Through a single interface, several ministries create community, cluster, and commercial biogas facilities to provide rural India with clean energy and sustainable fertilizers.

### SATAT

The SATAT plan supports the generation of Compressed Bio-Gas (CBG) from organic waste as a cost-effective, eco-friendly transportation fuel. The oil companies with guaranteed buybacks of CBG incentivize entrepreneurs to set up CBG plants and turn waste into a sustainable revenue stream.

### Way Forward

Biogas technology is a feasible renewable energy option for clean energy and waste management that could aid rural development by promoting sustainable agriculture and livelihoods. Biogas utilization in rural regions can improve the quality of life, sustainability, and energy security when the government and community work together.

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ISSN : 2583-0910

Agri-India TODAY

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Peer reviewed
monthly newsletter

Article ID : 06/VI/39/0626

# SMART FARMING REVOLUTION: HOW AI RESHAPING AGRICULTURE?

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## Abstract

As global food systems face the dual pressures of climate volatility and a shrinking rural workforce, Artificial Intelligence (AI) has transitioned from experimental pilots to a core driver of agricultural digitalization. Smart farming driven by AI is transforming traditional agriculture into a modern data-driven system. This study explores, how AI technologies such as machine learning, sensors, drones and robotics are improving agricultural productivity and sustainability. Smart farming uses real-time data from soil, weather and crops to help farmers to make accurate decisions related to irrigation, fertilization, pest control and harvesting. The integration of AI enables precision farming, crop prediction and early detection of plant diseases, leading to increased yields and reduced resource wastage. Additionally, automation and intelligent systems reduce labour dependency and improve efficiency in farm operations. This review concludes that AI offers a transformative pathway toward resource efficiency and food security. Its sustainable success depends on multisource data synchronization and development of cost-effective, localized AI solutions for diverse agricultural environments.

**Keywords:** Artificial intelligence, precision agriculture, sustainable farming, predictive analytics and resource optimization

## Introduction

The world of farming is currently going through a massive change by moving away from traditional methods tohigh-tech future. Futuristic ideas like Artificial Intelligence (AI) are now becoming the everyday tools that farmers need to survive. This change is happening because we face three big challenges: a fast-growing world population, unpredictable weather due to climate change and a shortage of natural resources like water and healthy soil. To keep up, farmers are using smart sensors (IoT) and satellites to watch their crops in real-time. This allows AI to act like a "digital brain" by making smart decisions that helps grow more food, while using fewer chemicals and less water. Today, these technologies are no longer just fancy gadgets but essential tools for feeding the world and protecting our planet at the same time (Aijaz *et al*., 2025 and Lakshmi and Corbett, 2020).

This digital transformation marks a major change in how farm moving from back-breaking manual labour and reacting to problems after they happen by using smart and datadriven strategies that can prevent issues before they start. By combining tools like Edge AI (smart local processing), drones (UAS) and predictive analytics, farming is reaching a level of accuracy never seen before. Instead of treating an entire field the same way, farmers can now practice "site-specific" management through giving each individual plant or small patch of soil exactly what it needs (Meegle, 2026; Frontiers, 2025).

The results of using this technology are huge and clear. Research shows that using AI to watch for pests in real-time and apply fertilizer or water only, where need can boost crop harvests by 15–20 per cent. At the same time, it cuts down the use of harmful chemicals by nearly 30 per cent. This shows that AI isn't just about making more money; it is a vital tool for protecting our environment and making farming sustainable for the future (Ahmad *et al*., 2026; Taylor & Francis, 2025).

Smart farming refers to the integration of advanced technologies such as AI, Internet of Things (IoT), sensors and robotics into agriculture. These technologies collect real-time data from farms and use it to optimize various farming activities like irrigation, fertilization and harvesting (Mmbando, 2025 and Yuan & Sun, 2025).

Despite of all these amazing benefits, moving toward a fully automated farm isn't easy for everyone. While big and wealthy farming companies are already using self-driving tractors and high-tech tracking to boost their profits while many smaller farmers are being left behind (Taneja *et al.,* 2023). This is known as the "digital divide". For small-scale farmers, the main problems are the very high cost of the equipment and the lack of basic needs like strong internet or stable electricity in rural areas. To truly succeed, the future of AI must focus on making these tools affordable and easy to use for everyone. If we can create local, low-cost solutions, we can make sure that the world has enough food in a way that is fair for every farmer, not just the big ones (Mishra and Mishra, 2024).

### Applications of AI in agriculture

AI, with its ability to process vast amounts of data and learn from it, is finding diverse applications across the entire agricultural value chain.

### 1. Precision farming

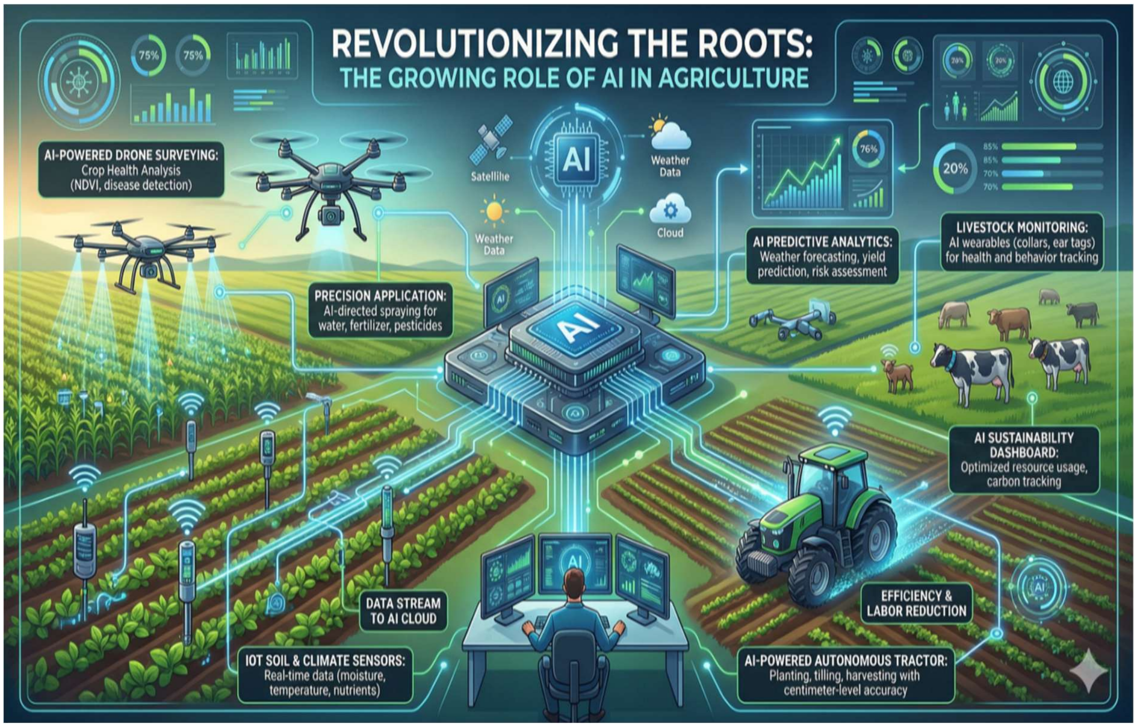
Precision farming uses AI to tailor agricultural practices for specific field conditions by moving away from a one-size-fits-all approach (Padhiary *et al*., 2025).

- **Variable rate application:** AI analyzes data from various sources (soil sensors, weather stations, satellite imagery) to create precise maps that instruct machinery on the optimal amount of water, fertilizer and pesticides for different parts of a field (Rahman*et al*., 2018). This maximizes resource use efficiency and reduce wastage (Treboux and Genoud, 2018 and Kiani & Seyyedabbasi 2018).
- **Weed and pest management:** AI-powered drones and ground vehicles equipped with computer vision can identify and target individual weeds or pests by enabling spot applications of herbicides and pesticides. This significantly reduces overall chemical use and minimize the environmental impact (Singh and Sobti, 2021 and MDPI, 2025).
- **Disease detection:** Algorithms trained on massive datasets of plant images can identify early signs of diseases in crops, often before they are visible to the human eye (Gobalakrishnan*et al.,* 2020). This allows for proactive intervention, preventing widespread outbreaks and crop losses (Sharma, *et al.,* 2020 and Sumithra*et al*., 2015).

### 2. Smart crop monitoring

AI is transforming crop monitoring from a labour-intensive, often reactive process into a data-driven proactive one.

- **Yield prediction:** AI analyzes historical data, weather patterns and real-time crop health data to generate accurate yield predictions. This helps farmers make informed decisions about harvesting, logistics and market entry (Ahuja and Mehra 2023).



- **Crop health analysis:** Computer vision techniques can be applied to images captured by drones and satellites to identify nutrient deficiencies, water stress and overall plant health. This enables timely and targeted interventions (Liopa-Tsakalidi*et al*., 2013).
- **Growth stages identification:** AI systems can accurately identify a crop growth stage, which allows farmers to optimize the timing of critical activities like irrigation and fertilization.

### 3. Autonomous farming

AI is paving the way for autonomous and semi-autonomous farm machinery, leading to increased efficiency and reduced labour dependence (Rajalakshmi and Mahalakshmi, 2016).

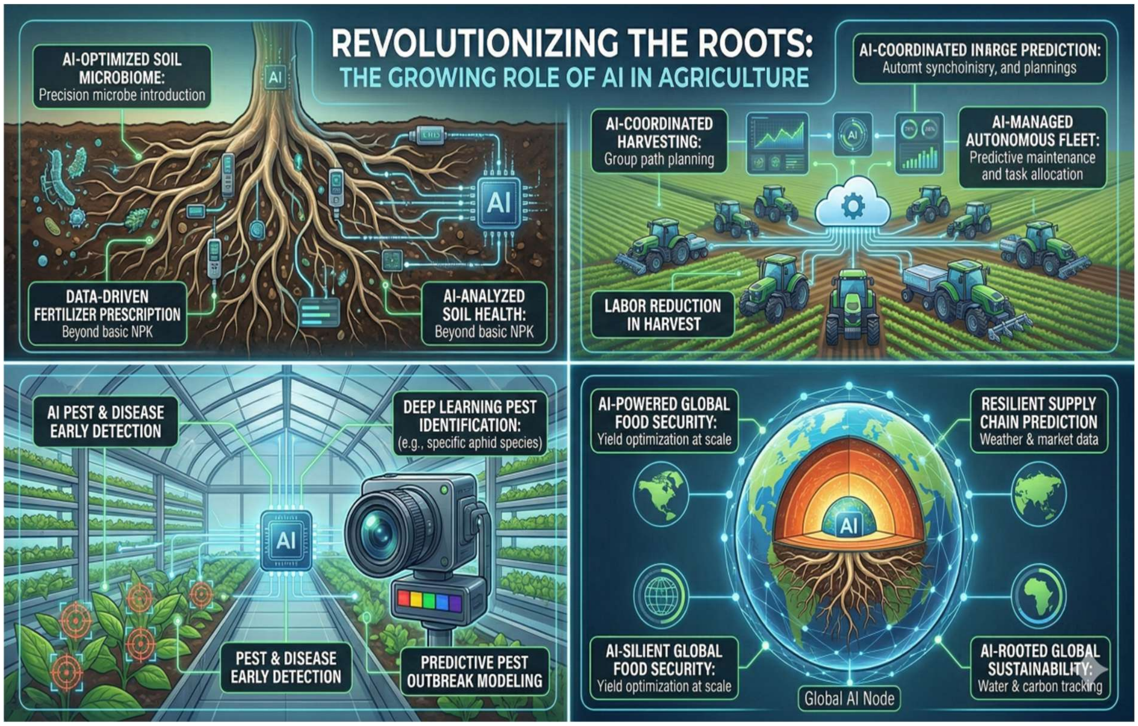
- **Autonomous tractors and harvesters:** Self-driven tractors and harvesters equipped with sophisticated sensor and navigation systems can operate with minimal human intervention. This not only increases operational efficiency but alleviates labour shortagesalso (Li & Wu,2016).
- **Robotic harvesting:** AI-powered robots with advanced computer vision and gripping technologies are being developed for tasks like delicate fruit and vegetable harvesting, where human labour is often in high demand (Elijah *et al*.,2018 and Li & Wu, 2016).

### 4. Supply chain management and logistics

AI is also making waves in agricultural logistics and supply chain management, improving efficiency and reducing waste (Ray.,2017 and Parasuraman*et al*., 2019)

- **Predictive analytics:** AI analyzes historical sales data, market trends and weather patterns to forecast demand and optimize supply chains. This helps to prevent food waste by ensuring that produce reaches to market when demand is high. (Encinas *et al*.,2017)
- **Traceability and quality control:** AI-based systems can trace produce from farm to fork by ensuring quality and safety through supply chain. This is crucial for maintaining consumer trust and ensuring food safety (Siddhartha and Lakkannavar, 2021).

- **Route optimization:** AI algorithms can optimize logistics and transportation routes, reducing fuel consumption and operational costs.



**Advantages of AI in agriculture**

- **Increased efficiency:** AI optimizes resource use, reduces waste and enhances operational efficiency, leading to higher yields and reduced production costs.
- **Enhanced sustainability:** Precise application of inputs reduces environmental impact and AI-driven monitoring helps conserve resources like water.
- **Improved crop yields:** Targeted interventions, early disease detection and optimized practices lead to increased crop productivity.
- **Labour savings:** Autonomous machinery and automated processes alleviate labour shortages, making agriculture more viable in areas with declining workforces.
- **Better decision-making:** Data-driven insights from AI systems empower farmers to make more informed and timely decisions (Nagaraja*et al.,* 2019).

**Challenges of AI in Farming**

- **High implementation costs:** The initial investment required for AI technology can be substantial, making it difficult for small and mediumsized farms to adopt.
- **Data privacy and security:** The vast amount of data generated by AI systems raises concerns about data privacy and security, as well as potential for misuse.
- **Digital Divide:** The adoption of AI in agriculture could exacerbate the digital divide, with large, tech-savvy farms benefiting more than small, resource-constrained ones.
- **Skills gap:** Implementing and maintaining AI systems requires a skilled workforce with expertise in both agriculture and technology, which is currently lacking in many areas.
- **Ethical considerations:** The use of autonomous machinery and AI in agriculture raises ethical questions about displacement of human labour and the potential impact on rural communities.

### Future of Smart Farming

The future of agriculture lies in fully automated and intelligent farming systems. AI will continue to evolve, integrating with drones, satellites and advanced analytics to create highly efficient farming ecosystems. Smart farming will not replace farmers but will empower them to become more strategic and productive. As technology becomes more accessible, even small-scale farmers will benefit from AI-driven solutions.

### Conclusion

The smart farming revolution driven by AI is transforming agriculture into a more efficient, sustainable and productive industry. By enabling precision farming, improving decision-making and reducing resource wastage. AI is helping farmers to meet the challenges of the modern world. As global demand for food continues to rise, adoption of AI in agriculture is no longer an option, it is a necessity for ensuring food security and environmental sustainability.The integration of AI into agriculture is not just about increasing efficiency, but it's about building a future, where food production is sustainable, secure and equitable.

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ISSN : 2583-0910
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Peer reviewed
monthly newsletter

Article ID : 06/VI/40/0626

# BEE POLLINATION AS A SERVICE: A SMART BUSINESS MODEL FOR MODERN AGRICULTURE

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## Abstract

Bee pollination is essential for the productivity, quality and ecological balance of agriculture. The loss of pollinators, loss of habitat and overuse of pesticides, however, have caused insufficient pollination, resulting in lower yields and losses for farmers. In this context, the services provided by bees are being perceived as an innovative model for sustainable agribusiness that incorporates the ecological conservation and commercial agriculture. This article delves into the idea of a managed bee pollination service as a service-based business to improve crop yield and foster climate-friendly agriculture. The establishment of healthy colonies of bees in the crop fields during flowering time can significantly enhance the efficiency of pollination processes, leading to better fruit set, seed quality and yield increase in some pollinator dependent crops of 20-40%. The article also features highlights on the business opportunities of organized pollination services, such as renting colonies, having a honey-bee subscription system, and generating extra income from selling honey, beeswax, and pollen products. In addition, the environmental values of bee pollination services, such as biodiversity conservation, and reduced reliance on chemicals and sustainable management of ecosystems are highlighted. The study suggests that managed bee pollination services are a low-cost, high-impact, and scalable approach to ensuring sustainable agriculture, rural entrepreneurship and long-term food security.

**Keywords:** Bee Pollination Services, Sustainable Agriculture, Crop Productivity, Agribusiness Model, Pollinator Management

## Introduction

Pollination is a key ecosystem service that contributes to crop productivity. Bees are the most important pollinators for many crops, where they are responsible for much of the successful fertilization, fruit set, seed development and improvement in quality. Bee pollination is used directly or indirectly in the production of almost one-third of the world's food. But in the modern agriculture, the bee population has been in decline, habitats are being destroyed and heavy use of pesticides have caused a serious pollination gap. The shortage of pollination has become a silent factor affecting the productivity of crops and their quality, and compromising farmer's profits in many farming systems. To overcome this, the pollination service of bees is becoming more relevant as an innovative and sustainable agribusiness model. Managed colonies are strategically placed in the crop fields during the flowering stage to increase the efficiency and productivity of pollination services. Plumage Bee Pollination services play a vital role in enhancing the agricultural production in addition to aiding in the conservation of biodiversity, sustainable farming techniques, and job creation in rural areas.

## The Growing Need for Bee Pollination Services

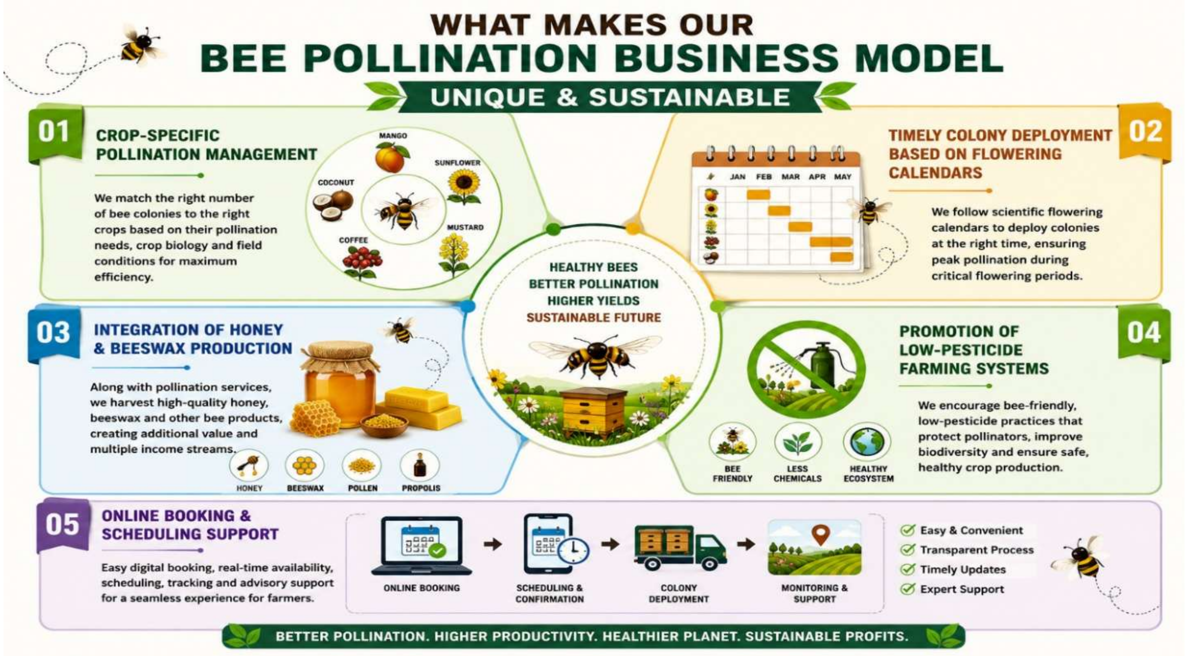
Loss of natural pollinators due to habitat loss, climate change, mono cropping and unsustainable pesticide use is becoming a challenge for modern agriculture with a reduced natural pollinator population. Insect pollination is critical to produce fruit, seed, and improve the quality of many important crops. Inadequate pollination can lead to yield loss, poor fruit size and uniformity, poor seed viability and lower market value which can impact the farmer's earning. In this context, the role of bee pollination has proved to be an effective and viable way of farming. Managed bee colonies can be deployed at the flowering time of the crop, which can significantly boost pollination efficiency, thereby increasing production, crop quality and profitability; and contribute to biodiversity conservation and environmentally friendly farming practices.

**Bee Pollination as a Sustainable Agribusiness Model**

The bee pollination service is becoming a new and viable agribusiness opportunity offering both eco-services and economic profit. In this situation, farmers lease bee colonies from beekeepers for seasonal or subscription years. The distinctive characteristic of this business model is:

- Crop-specific pollination management
- Proper timing of the deployment of colonies using flowering calendars
- The integration of the production of honey and beeswax.
- Pesticide farming systems promoted as low levels of pesticides are used.
- Online booking and scheduling assistance.

Pollination services offer several income streams and are an integral part of agricultural sustainability, as compared to traditional beekeeping that only seeks to harvest honey.



**A systematic approach for effective pollination management**

- **Initiating healthy hives:** The implementation of bee pollination services starts with the establishment of bee colonies in strong and healthy apiary units that are able to pollinate efficiently.
- **Crop Clusters and Flowering Seasons Identification:** The concentration of pollinator dependent crops like sunflower, coconut, mango, mustard, drumstick etc is used to identify

suitable crop growing regions. Flowering calendars are produced to establish the best time for making colonies.

- **Deployment of Bee Colonies in Fields:** Managed colonies of bees are purposefully located in crop fields during the flowering period to provide the most pollination service. Based on the farmer's need and farm size, the colonies are used on rental or subscription basis.
- **Conserving pollinators and promoting farmer awareness for pollinator-friendly practices:** Farmers are given information about the value of pollinators and taught how to better manage their agricultural practices to enhance the value of pollinators, including reduced use of pesticides in flowering periods, keeping flowering plants and adhering to safe spray schedules.
- **Monitoring and Post-Pollination Management:** Bee activity and colony health are monitored regularly during the pollination period to guarantee good performance. After completion of flowering, colonies are safely retrieved and relocated to other suitable forage areas for continued utilization and honey production.

| S.NO | CROP/TREE | NECTAR | POLLEN | LOCATION | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | Coconut | ++ | ++ | Thanjavur , Pollachi | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 |
| 2 | Rubber | ++ | + | Kanyakumari |  | 🟩 | 🟩 |  |  |  |  |  |  |  |  |  |
| 3 | Neem | ++ | + | All districts |  |  | 🟩 | 🟩 |  |  |  |  |  |  |  |  |
| 4 | Sunflower | +++ | ++ | Madurai, Virudhunagar | 🟩 | 🟩 |  |  |  |  |  |  | 🟩 | 🟩 |  |  |
| 5 | Mustard | +++ | ++ | Dharmapuri | 🟩 |  |  |  |  |  |  |  |  |  |  | 🟩 |
| 6 | Mango | ++ | + | Krishnagiri , Salem | 🟩 | 🟩 |  |  |  |  |  |  |  |  |  |  |
| 7 | Drumstick | ++ | + | Theni , Karur |  |  | 🟩 | 🟩 |  |  |  |  |  |  |  |  |
| 8 | Eucalyptus | +++ | + | Nilgiris , Salem | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 |
| 9 | Jamun | +++ | ++ | Vellore , Dharmapuri |  |  | 🟩 | 🟩 |  |  |  |  |  |  |  |  |

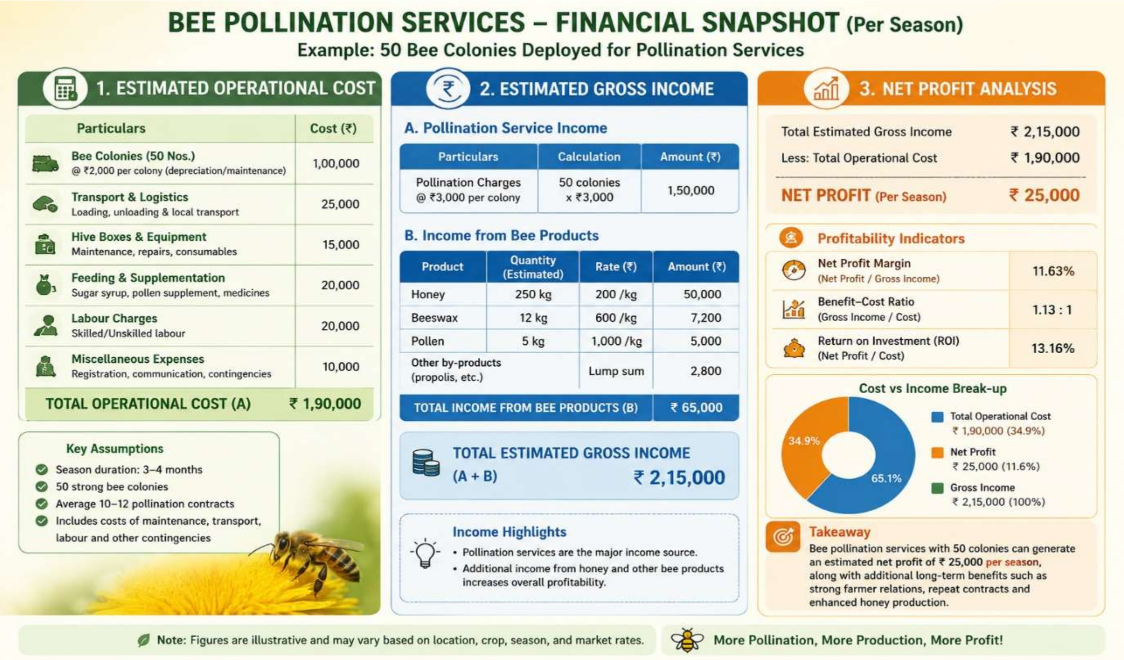
**Figure:** The **Tamil Nadu Flora Chart for Beekeepers** highlighting the seasonal availability of major nectar and pollen-rich crops and trees across different regions of Tamil Nadu

### Target Beneficiaries of Pollination Services

The contributions of bee pollination services are beneficial for many different groups of agricultural stakeholders as it enhances the yield, quality and profitability of the crops. Effective pollination at low cost, increases productivity and income of small and marginal farmers. Better fruit set and quality in plantation crop growers of coconut, coffee, mango and rubber crops. For seed production farmers, it is the use of bee pollination to improve seed viability and efficiency of cross pollination. Collective pollination services can be implemented within cluster-based farming systems by the Farmer Producer Organizations (FPOs), and pollination support for organic and sustainable farming practices can be provided in an eco-friendly way. Furthermore, pollination services generate good job and business creation opportunities in rural areas for the rural youth and agripreneurs in the management of bee-colonies, honey production and pollination service operations.

### Economic Potential of Bee Pollination Services:

The infographic highlights the strong economic potential of bee pollination services as a sustainable agribusiness model. With relatively low operational costs and multiple income sources such as pollination services, honey, beeswax, and pollen products, the enterprise generates attractive profits and a favourable benefit-cost ratio. The analysis demonstrates that managed bee pollination is not only environmentally beneficial but also financially viable, offering recurring income opportunities for farmers, beekeepers, and rural entrepreneurs.



**BEE POLLINATION SERVICES – FINANCIAL SNAPSHOT (Per Season)**

Example: 50 Bee Colonies Deployed for Pollination Services

**1. ESTIMATED OPERATIONAL COST**

| Particulars | Cost (₹) |
|---|---|
| Bee Colonies (50 Nos.)<br>@ ₹2,000 per colony (depreciation/maintenance) | 1,00,000 |
| Transport & Logistics<br>Loading, unloading & local transport | 25,000 |
| Hive Boxes & Equipment<br>Maintenance, repairs, consumables | 15,000 |
| Feeding & Supplementation<br>Sugar syrup, pollen supplement, medicines | 20,000 |
| Labour Charges<br>Skilled/Unskilled labour | 20,000 |
| Miscellaneous Expenses<br>Registration, communication, contingencies | 10,000 |
| TOTAL OPERATIONAL COST (A) | ₹ 1,90,000 |

Key Assumptions

- ✓ Season duration: 3–4 months
- ✓ 50 strong bee colonies
- ✓ Average 10–12 pollination contracts
- ✓ Includes costs of maintenance, transport, labour and other contingencies

**2. ESTIMATED GROSS INCOME**

A. Pollination Service Income

| Particulars | Calculation | Amount (₹) |
|---|---|---|
| Pollination Charges @ ₹3,000 per colony | 50 colonies x ₹3,000 | 1,50,000 |

B. Income from Bee Products

| Product | Quantity (Estimated) | Rate (₹) | Amount (₹) |
|---|---|---|---|
| Honey | 250 kg | 200 /kg | 50,000 |
| Beeswax | 12 kg | 600 /kg | 7,200 |
| Pollen | 5 kg | 1,000 /kg | 5,000 |
| Other by-products (propolis, etc.) | | Lump sum | 2,800 |
| TOTAL INCOME FROM BEE PRODUCTS (B) | | | ₹ 65,000 |

TOTAL ESTIMATED GROSS INCOME (A + B) ₹ 2,15,000

Income Highlights

- Pollination services are the major income source.
- Additional income from honey and other bee products increases overall profitability.

**3. NET PROFIT ANALYSIS**

| | |
|---|---|
| Total Estimated Gross Income | ₹ 2,15,000 |
| Less: Total Operational Cost | ₹ 1,90,000 |
| NET PROFIT (Per Season) | ₹ 25,000 |

Profitability Indicators

| | |
|---|---|
| Net Profit Margin (Net Profit / Gross Income) | 11.63% |
| Benefit–Cost Ratio (Gross Income / Cost) | 1.13 : 1 |
| Return on Investment (ROI) (Net Profit / Cost) | 13.16% |

Cost vs Income Break-up

Takeaway

Bee pollination services with 50 colonies can generate an estimated net profit of ₹ 25,000 per season, along with additional long-term benefits such as strong farmer relations, repeat contracts and enhanced honey production.

Note: Figures are illustrative and may vary based on location, crop, season, and market rates.

More Pollination, More Production, More Profit!

## Challenges in Bee Pollination Services

There are some problems associated with bee pollination services that can impact the effectiveness of these services and large-scale uptake. Bee losses and reduced colony survival may be significant when pesticides are applied to crop in excess during the flowering stage. Bee activity and pollination efficiency also decreases due to changing climate, loss of habitat and seasonal changes in floral resources. Furthermore, the lack of awareness among farmers on the necessity of pollination by the bees, and the problems of transferring colonies and moving them, as well as the limited number of trained pollination service providers, help to limit this business. Sustainable pollination management is needed to overcome these challenges by farmer education, pollinator-friendly practices and policy support.

## Future Scope and Opportunities

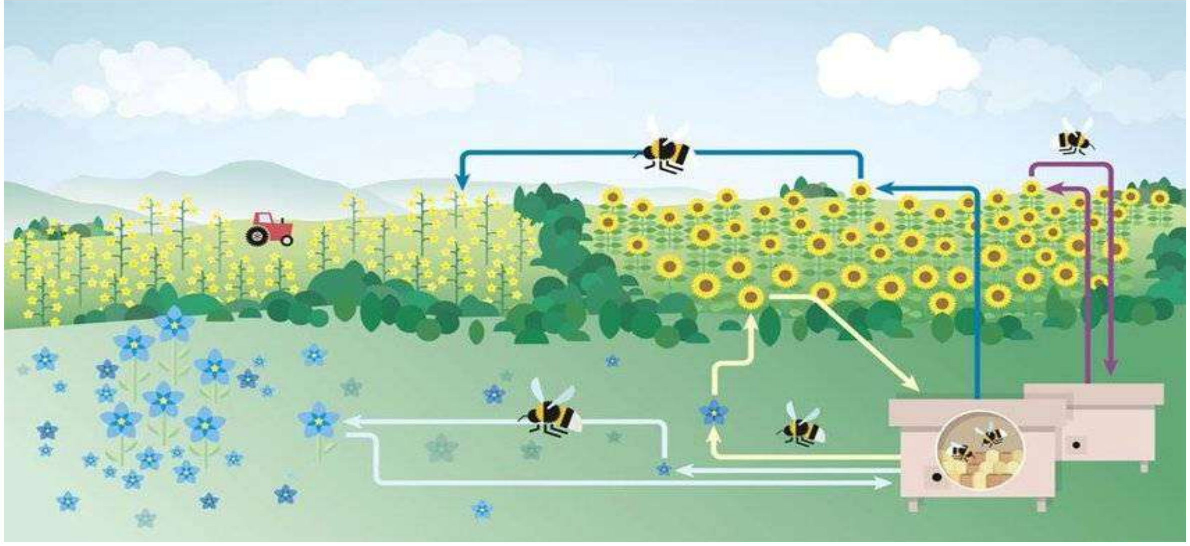
The current scenarios are very promising for bee pollination services as sustainable agriculture and quality food production grows. Emerging opportunities include:

- Digital platforms for pollination booking.
- Precision pollination services
- The integration with the organic farming system
- FPO-based pollination networks
- Government-supported pollinator missions
- The export-oriented quality systems of production

As more and more people become aware of the need for ecological farming, bee pollination can be an important part of a climate-smart agriculture programme.

## Conclusion

Bee pollination is a low-cost, high impact and environmentally sustainable innovation in agriculture. Managed pollination offers advantages to both farmers and consumers, as well as to ecosystems, by increasing crop yields, improving product quality, benefiting biodiversity, and providing employment in rural areas. In the context of the challenges posed by climate change, biodiversity depletion and soil health challenges in agriculture, bee pollination can be seen as a viable option for resilient and sustainable crop production. Pollinators' conservation is no longer just an environmental issue and now essential for food security and rural growth.



**"Rent a Hive, Reap the Harvest"**

ISSN : 2583-0910
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Peer reviewed
monthly newsletter

Article ID : 06/VI/41/0626

# SMART PEST MANAGEMENT INNOVATIONS IN AGRICULTURE

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## Introduction

The adoption of '*Green Revolution*' by India in the late 1960s was an epitome of success, courage, dedication and willpower put upon by a newly liberated nation. Green revolution heavily relied on the use of chemical fertilizers, pesticides, high yielding varieties, irrigation, farm mechanization and improved scientific methods of cultivation for increasing the agricultural production. From surviving the ravages of the devastating '*Bengal famine*' of 1943 to securing the spot among self-sufficient nations in food grain production, Indian agriculture has evolved a lot. But this extensive cultivation model involving the unregulated use of synthetic chemicals has simultaneously resulted in the deterioration of the environmental quality and exhaustion of its resources. These harmful chemicals have now found access to our soil, ground water, rivers, oceans, air and food resulting in *bio-accumulation* and *bio-magnification* in the ecosystem.

Over the past few decades, the global population has been significantly sensitized to environmental protection and food quality assurances. The mainstream agriculture is now embracing organic farming which primarily focuses on maintaining the health of consumers as well as the quality of soil and environment by substituting the use of synthetic chemicals with relatively non-toxic and sustainable crop production inputs like biofertilizers, vermicompost, biopesticides, processed farm wastes or crop residues, green manures, etc. Organic farming essentially employs prophylactic pest management strategies which are environmentally sustainable, cheap and ecofriendly. Hence, it is high time to accept the fact that, spraying of synthetic chemicals is not the only measure available for controlling notorious agricultural pests. These problems can be collectively addressed by fostering natural enemies and by providing suitable environment for crop growth in such a way that positively improves the tolerance and resistance levels in crops. We must change our agricultural habits by integrating readily adoptable, cost effective and eco-friendly pest management alternative such as *Bio-intensive Integrated Pest Management* (BIPM) and ecological pest management like *Push-Pull strategy*. Considering the massive stride taken by India in the field of science and technology, it becomes imperative to develop and adopt novel pest management technologies such as *Artificial Intelligent pest attraction traps* (A.I. traps), RNA- *induced gene silencing* and intervention of nanotechnology for betterment of agriculture.

## The Problem

It has been reported that, less than *1 per cent* of the active ingredient used in pest management reaches the target (Pimentel, 1995) while the rest ends in the ecosystem either through drift and evaporation (50%), surface roll off (30%), environmental breakdown (15%) and bounce off (5%) (Yin *et al.*, 2023). The irrational use of pesticide have resulted in development of pesticide resistance, pesticide residues in edible plant parts and elimination of the beneficial organisms from the environment leading to frequent pests outbreaks (Rai and Sarkar, 2018). Further, there are several tragic instances in history involving mishandling of agricultural chemicals which revealed their actual unseen toxicity (*acute* and *chronic*) that remains unquantifiable till date. The Minamata disease (*Minamata prefecture, Japan,* 1956) caused due to bioaccumulation of Methyl Mercury in fish, Bhopal gas tragedy (*Bhopal, India,* 1984) involving leakage of highly toxic Methyl isocyanate (MIC) gas used for manufacturing carbaryl, Blue baby syndrome (*Methaemoglobinaemia*) due to nitrate accumulation in ground water resulting from the use of synthetic fertilizers in agriculture and the horrific terror associated with the Kasargod episode of Keralam, India (1970 to 2000) involving the aerial spraying of Endosulfan include some classic examples worth mentioning in this context. In 2026, a total of 372 pesticides and 1177 formulations has been registered under section 9(3) of the Insecticides Act, 1968 for use in India while 46 pesticides has been banned and **16** pesticides has been restricted for use in the country (PPQS, Government of India). In 2020, the total global pesticides use in agriculture was estimated at 2.7 million tonnes (Mt) of active ingredients, where India ranked **9th** among the top 10 largest pesticide using nations (Anonymous, 2020).

## The Solution

### A) Bio-intensive Integrated Pest Management (BIPM)

Historically, the management strategies of agricultural pest have been grouped into three distinct phases *viz.*, the *era of traditional approaches* (prior to 1939), the *era of pesticides* (1939 to 1975) and the *era of Integrated Pest Management* (1975 onwards) (Metcalf, 1980). While discussing Integrated Pest Management (IPM), the organochlorine insecticide dichloro-diphenyl-trichloroethane (DDT) holds a very indispensable position in the timeline as it is directly responsible for the inception of IPM. DDT was synthesized by Austrian chemist, *Othmar Zeidler* in 1874, but its insecticidal property was discovered Swiss chemist, *Paul Hermann Müller* in 1939. However, the first documented use of DDT is recorded as a chemical of vector control for Malaria (mosquito) and Typhus (head lice) during the second world war (1943–1945) by United States military. After the war, Paul Hermann Müller was awarded with the honour of *1948 Nobel Prize in Medicine* for his revolutionary discovery and DDT was unanimously declared a miracle chemical for use in agriculture worldwide. However, the fame did not last long as the publication of '*Silent Spring*' by biologist *Rachel Carson* in 1962 openly named and shamed the ill effects of DDT on the environment and ecosystem. The worldwide attention to this matter paved the way for the establishment of the *U.S. Environmental Protection Agency* (EPA) in 1970 which banned the nation-wide use of DDT in 1972. Globally, the production and agricultural use of DDT are banned under the *2004 Stockholm Convention on Persistent Organic Pollutants*. Today, India is the sole country that produces DDT for disease vector control in sub-Saharan Africa.

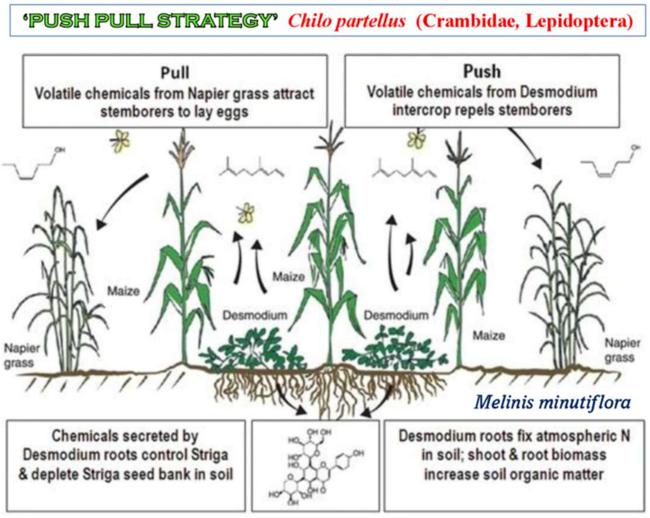
During the 1970s, the concept of IPM was first introduced by *Ray F. Smith* (*1997 World Food Prize laureate*) who emphasized more on supressing the population of pests below damaging levels rather than eliminating their entire population. IPM is a pest management strategy that simultaneously employs easily available and adoptable pest management tactics viz., cultural, mechanical, biological, genetic, chemical, Host Plant Resistance (HPR), etc to supress the pest population and maximize the economic output with minimum adverse effect on the environment and human health. Later, Frisbie and Smith (1991) proposed *Biointensive IPM* (BIPM) which mostly rely on host-plant resistance, biological control and cultural control. It basically aims to reduce the use of synthetic pesticides by substituting them with biopesticides (microbial and botanical orgin), biocontrol agents (parasites, parasitoids, predators) and all conventional nonchemical methods of pest control. The benefits of implementing biointensive IPM can include reduced chemical input costs, reduced on-farm and off-farm environmental impacts, and more effective and sustainable pest management (Reddy, 2014).

### B) Ecological pest management: 'Push Pull Strategy'

It is a low cost, eco-friendly, economic and sustainable pest management technique formulated by the scientists of *International Centre of Insect Physiology and Ecology* (ICIPE), *Nairobi, Kenya* for ecologically managing the population of notorious Maize stem borer (*Chilo partellus;* Crambidae, Lepidoptera). It involves the simultaneous use of trap crop and repellent crop for attraction (PULL) and repulsion (PUSH) of the target pest within the agro-ecosystem. The components of the strategy are discussed below.

I. **Repellent crops:** Silver leaf desmodium (*Desmodium uncinatum*) or Molasses grass (*Melinis minutiflora*) is grown as '*intercrop*' that release volatile chemicals and repels the stem borers from the main crop. Desmodium does not interfere with the growth of maize, but can suppress weeds and can help to enhance soil fertility by stabilizing soils, increasing soil organic matter content and fixing nitrogen. It also serves as a highly nutritious animal feed and effectively suppresses striga weeds.

II. **Trap crops:** Napier grass (*Pennisetum purpureum*), Signal grass (*Brachiaria brizantha*) and Sudan grass (*Sorghum vulgare sudanense*) are planted as '*border crop*' around the maize and sorghum fields as trap crops which release volatiles and attract the adult stem borer moths, reducing the damage on main crop.



*Reference:* ICIPE, Nairobi, Kenya

### C) Artificial intelligent pest attraction traps (AI Traps)

Basically, insect traps can be grouped into two categories viz., *Attraction traps* (uses attractant to attract the insect *eg*. Light trap, Pheromone trap, Bait trap, Yellow sticky trap, etc) and Interception traps (eg. Suction trap, Pitfall trap, Window pane trap). These traps over time have been modified to catch up with the most recent technological advancements in the field of Artificial Intelligence. Such AI traps are equipped with modern technologies (AI software, camera, GPS sensors, cloud connectivity, multimedia storage chip, solar panel, battery, micro controllers and microprocessors) enabling automatic pest monitoring (identify, classify and quantify) in the field. AI-enabled traps provided robust, location-specific monitoring of pest dynamics, delivering reliable early-warning data to optimize pesticide applications. This approach reduces unnecessary spraying, mitigates environmental contamination, and supports region-specific integrated pest management strategies

(Itmec and Zorlu, 2025). Some of the novel innovations worldwide in the relevant field are as follows.

I. **AI Pheromone trap** (ICAR-CICR, Nagpur): A camera-based AI pheromone trap has been developed by *Central Institute for Cotton Research* (ICAR-CICR), Nagpur for managing the notorious pink bollworm (*Pectinophora gossypiella*; Gelechidae, Lepidoptera) infesting cotton. The trap consists of Pheromone lure (*Gossyplure*) as an attractant, a camera sensor with LED illuminator for taking pictures and counting the trapped insect in the sticky liner and a solar panel fitted to a battery for power supply. Artificial Intelligence technology specially developed for precise pest population monitoring then analyses these captured images using a machine learning algorithm, trained to identify and count pink bollworms caught in traps. Finally, the farmers will receive pest alert information (Economic Threshold Level) in real-time via their mobile phone application.

II. **Pied Piper trap** (Vaughn *et al.*, 2024): This A.I. attraction trap has been developed for monitoring the Buffalo Tree hopper (*Stictocephala basalis*; Membracidae, Hemiptera). It is a polyphagous species feeding mostly on woody perennials (apple, grapes, willow, peach, pear, and oak) which was recently reported for the first time in India from Kashmir (Madhanram *et al.*, 2025). The principal components of the trap consist of Control system (recording audio & pest detection), Power unit (Solar cells + Battery), Input audio (Piezoelectric contact microphone), Output audio (Vibration exciter) and Imaging unit (Camera + LED light). The device detects male treehoppers by sensing their mating calls using a piezoelectric contact microphone attached to a host plant, and lures them towards an imaging area by playing a prerecorded female mating call using a vibration exciter.


*Fig*: **Pied piper trap** (Vaughn *et al.*, 2024)

III. **DIY (do-it-yourself) camera trap** (Sittinger *et al.*, 2024)**:** Scientists at the *Federal Research Centre for Cultivated Plants*, Germany have recently developed '*Insect detect*' which is an open-source DIY camera trap capable of automatic monitoring of flower visiting insects based on low-cost off-the shelf hardware components combined with open-source software. The trap is equipped with custom trained deep learning models that detect and track insects landing on an artificial flower platform in real time and accurately classify the insects which is used to estimate the insect activity or abundance.


*Fig.* Insect Detect: DIY trap (Sittinger *et al.*, 2024)

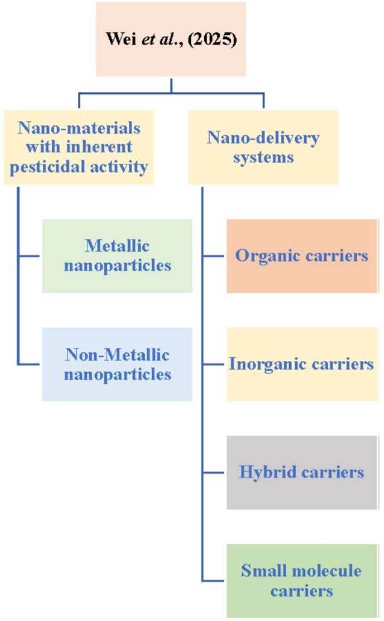
IV. **iMETOS iSCOUT®** (Itmec and Zorlu, 2025): It is an AI-enabled camera-based pheromone trap developed by scientists at *Çukurova University*, Adana, Turkey capable of automatically detecting orchard pests and capturing high-resolution images of the trapped insects (on sticky trap surface) to be processed through AI-based algorithms for pest identification and counting.

1-Control unit, 2-Power supply (solar panel and battery)
3-Logger and modem, 4-Trap

Fig. Camera based pheromone trap for orchads (Itmec and Zorlu, 2025)

### C) Intervention of Nanotechnology

Nanotechnology is the manipulation of matter at the atomic scale with diameter ranging between 1 to 100 nanometers (nm) resulting in exceptionally high surface area-to-volume ratio that makes them highly reactive and significantly different from its bulk material in terms of physical and chemical properties. The prospective use of nanoscale agrochemicals such as nanofertilizers, nanopesticides, nanosensors and nanoformulations in agriculture has transformed traditional agro-practices, making them more sustainable and efficient (Neme *el al.*, 2021). Nanopesticides are nanostructures with two to three dimensions between 1 to 200 nm, used to carry agrochemical ingredients (Chaud *et al.,* 2021). In simple terms, nanopesticides are formulations intended for use in agriculture that contain nanoparticles as an active ingredient (a.i.) or as a carrier of toxic a.i. The main objectives of the nanopesticide formulations are enhanced solubility, controlled release of a.i. and targeted delivery of the payload under specific environmental triggers such as light, temperature, pH, moisture, enzymes, etc. Nanopesticides are highly advantageous over conventional pesticides as the controlled release mechanism ensure sustained delivery of the pesticide a.i. over a longer period of time significantly reducing the dosage and frequency of application. Consequently, this reduces the residues in crop produce, adverse effects on the natural enemies and ultimately achieves lower cost of production.



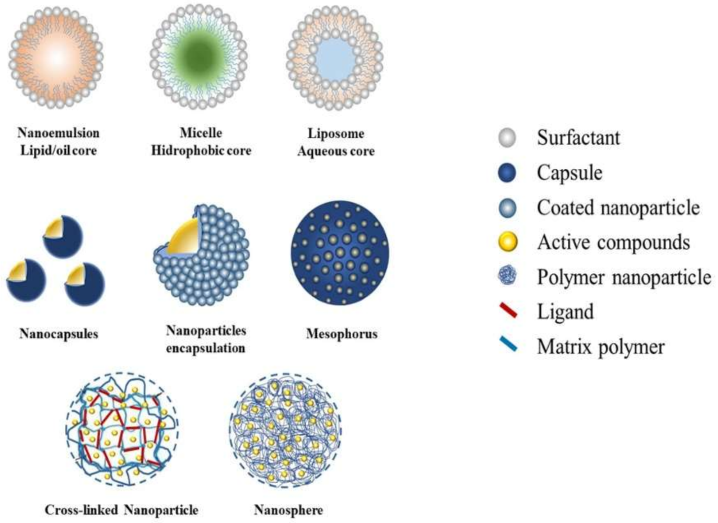


***Fig***: *Formulations of nano insecticides* *Classification of nano insecticides* (Wei *et al.*, 2025)

### D) RNA-induced gene silencing or RNA interference (RNAi)

RNA interference (RNAi) is a naturally occurring gene silencing mechanism conserved across organisms with a clearly defined cell nucleus (eukaryotes). *Andrew Fire* and *Craig Mello* discovered the mechanism of RNA interference (RNAi) in 1998, for which they were awarded the *2006 Nobel Prize in Physiology or Medicine*. Recently, the potential of RNAi to protect crops against insect pests has been explored by numerous scientists worldwide with remarkable findings that orally delivered dsRNA can induce an RNAi response in some insect species (Singh *et al*., 2013; Tayler *et al.*, 2019; Jacques *et al.*, 2020). Using RNAi for crop protection is especially attractive because of its high specificity which minimizes unintended effects on non-target organisms and improves the safety profile of RNAi products (Velez *et al.*, 2024).

### Mechanism of interference

I. **Loading of double-stranded RNA** (**dsRNA**): Designing a dsRNA with complementary sequence to a targeted mRNA encoding a vital protein for the insect survival or development.
II. **Enzymatic cleavage**: Upon introduction of dsRNA in the insect body, an enzyme called 'Dicer' cleaves it into tiny fragments with 21-25 nucleotides known as small interfering RNAs (siRNAs) or microRNAs (miRNAs).
III. **Complex binding:** The siRNA is loaded into a multiprotein complex called RISC (RNA-Induced Silencing Complex) which uses one of the siRNA strands as a guide to seek out and bind to its exact complementary mRNA sequence.
IV. **Degradation of mRNA**: The protein, Argonaute inside RISC acts as molecular scissors to cleave the bound mRNA halting its translation and successfully silencing the target gene.

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ISSN : 2583-0910
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Article ID : 06/VI/42/0626

# EMPOWERING COLD CHAIN INFRASTRUCTURE THROUGH FINANCIAL ASSISTANCE BY THE NATIONAL HORTICULTURE BOARD

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The National Horticulture Board (NHB) was set up by the Government of India in 1984 as an Autonomous organization under the administrative control of Ministry of Agriculture and Farmers Welfare and registered as a society under Societies Registration Act with its headquarters at Gurugram. Presently, NHB has 29 field offices located all over the country . **The present Managing Director of NHB is Sh. Kapil Meena, IAS.**

The broad aims and objectives of the Board are to develop production clusters/hubs for integrated Hi-tech commercial horticulture, development of post-harvest and cold chain infrastructure, ensuring availability of quality planting material and to promote adoption of new technologies/tools/ techniques for Hi-tech commercial horticulture etc. In India, the market trends for cold Storage facility providers are witnessing significant growth and transformation. With the rise of e-commerce and the increasing demand for temperature-controlled storage and logistics solutions, companies in the cold storage industry are focusing on expanding their infrastructure and adopting advanced technologies. Additionally, there is a growing emphasis on integrating cold chain networks to ensure seamless transportation and storage of perishable goods across the country.

**Capital Investment subsidy scheme for construction/expansion/ modernization of cold storage and storages for Horticulture Produce.**

**Components & Capacity:** Credit linked projects relating to Cold Storages including Controlled Atmosphere (CA)and their modernization are eligible for assistance under this component and storage capacity above 5001 MT up to 20000 MT.

**Pattern of Assistance: The assistance will be given as subsidy @ 35% of the capital cost of project in general areas. The maximum subsidy of Rs 285.60 for 10000 MT capacity.**

**Revised Cost Norms:**

| S. No | Description | Cost Norms |
|---|---|---|
| 1 | **Cold storage units Type 1**<br>i) Cold Storage Type-I is defined as CS-1 with Construction in civil including PUF/PIR panels, Doors and Ante-rooms, Refrigeration Units, Electrical Installation, Administrative block, Safety/Fire Safety and Hazard control and basic mazzenine structure<br>(For other component details please refer to NCCD guidelines) | NHB to take up projects with capacity above 5000 MT and upto 20,000 MT as per following rates: •<br>@ Rs. 9120/MT for capacity between 5001 to 6500 MT.<br>@ Rs. 8640/MT for capacity between 6501 to 8000 MT.<br>@ Rs. 8160/MT for capacity between 8001 to 10,000 MT.<br>@ Rs. 4080/MT for capacity between 10001 to 20000 MT |

| S. No | Description | Cost Norms |
|---|---|---|
| 2. | ii) Cold Storage Type-I is defined as CS-1 with Construction in combination of civil & PEB including PUF/PIR panels, Doors and Ante-rooms, Refrigeration Units, Electrical Installation, Administrative block, Safety/Fire Safety and Hazard control and basic mazzenine structure | • @ Rs. 11400/MT for capacity between 5001 to 6500 MT. •<br>• @ Rs. 10800/MT for capacity between 6501 to 8000 MT. • @ Rs. 10200/MT for capacity between 8001 to 10,000 MT. @ Rs. 5100/MT for capacity between 10001 to 20,000 MT. |

**Note: More details please visit NHB WEBSITE <u>www.nhb.gov.in</u> and refer to NCCD guidelines)**

राष्ट्रीय बागवानी बोर्ड
NATIONAL
HORTICULTURE BOARD

**Revision in the scheme guidelines of NHB, including its implementation design, documentation and sanctioning process**

The scheme guidelines of NHB including its implementation design, documentation and sanctioning process etc. have further been reviewed and with the approval of competent authority, it has been decided to effect major changes w.e.f. 01.01.2023. NHB will do away with two stage system of IPA and GoC. Now IPA will not be needed for availing benefit under the Scheme of NHB and applicant will apply straightaway for Grant of Clearance (GoC) to NHB after sanction of term loan by bank. The term loan sanctioned within 3 months from the date of online GoC application to NHB shall be treated valid, however, disbursement of term loan and start of project will be allowed only after issuance of GoC by NHB. GoC will be valid for 3 months for getting disbursement of first instalment of term loan and start of project. Accordingly, the applications in NHB will be dealt in the following manner

1. IPA system will be discontinued from 15.03.2023 and thereafter NHB shall accept applications only for Grant of Clearance with required documents. IPA/GoC applications received prior to the same will be considered as per existing system.
2. The processing of GoC application will be completely digital, including examination and sanctioning. The platform will be augmented with the timeline monitoring systems, so that every step can be monitored as per the pre-set target timelines and alerts can be sent to the

processing officer/applicant at regular intervals and escalation matrix can be put in place based on ageing analysis of pendency at officer level.

3. Before making a new GoC Application online on the Web-Portal of NHB, the applicant will have to register after Aadhar authentication through OTP verification. Applicant will be given an option at NHB portal and in case loan for the proposed project is sanctioned under Agri-Infra Fund (AIF) Scheme, the entire loan data of the applicant will be captured as such from AIF portal through API and only remaining details would be required to be filled in by the applicant online and saved at NHB Portal to complete the GoC application of NHB. In case loan is not sanctioned under AIF, the complete application form will have to filled up by the applicant.
4. NHB has prescribed a new short template for DPR and Bank appraisal note (Annexure-I). The template is indicative, and applicant/bank must ensure that the components mentioned in the template are invariably included in DPR or appraisal note.
5. The applicant will have to submit following documents along with the application for grant of clearance: - a. Details Project Report (DPR) and the information suggested in the NHB's prescribed template will only be mandatory. b. Project Land Document along with non-encumbrance certificate c. Bank Sanction letter d. Bank Appraisal Note e. Undertaking (will be part of Application Form in the prescribed format)
6. After application is submitted, an email will be sent to the applicant along with a reply/confirmation link to the financing bank. Concerned bank need to confirm the authenticity of documents online. Based on the confirmation of documents, e.g. bank sanction letter, appraisal note and land documents etc., NHB will issue GoC.
7. Queries on GoC applications, if any, will be communicated to the applicant Bank automatically by system/email by the concerned division within 15 days from the date of receipt of hard copy of the application/documents/bank documents and get the reply from applicant/bank within 15 days and place the application to the approving authority for decision. GoC will be issued by NHB within a period of two months positively.
8. Subsidy claim documents will also be submitted by bank/applicant online.
9. Technical Data sheet for Cold Storages and Protected Structure will be a part of DPR and instead of their appraisal by National Centre for Cold Chain Development or any other agency, it will be mentioned in the GoC Letter that applicant will construct the cold storage/green house as per extant standards/ specifications prescribed by NHB. Similarly, Registration certificate/Deed in case of legal entity will be a part of DPR.
10. NHB shall be timely relying upon financing banks for the examination of project documents.

**For more details, visit www.nhb.gov.in**

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ISSN : 2583-0910
Agri-India TODAY
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Article ID : 06/VI/43/0626

# THE IMPACT OF CLIMATE CHANGE ON THE AGRICULTURAL SECTOR: A CRISIS OF SUSTAINABILITY

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## Introduction

Agriculture is more than a source of sustenance; it is the foundation of global stability and the survival of human civilization. However, as rising temperatures and erratic weather patterns rewrite the rules of nature, once-fertile lands are increasingly at risk of becoming barren. Climate change is not a singular event but a systemic disruption of the entire agricultural value chain—from soil microbiology to the stability of global markets.

**The Four Principal Disruptors**: Climate change acts as a "threat multiplier" through four primary channels:

**Phenological Shifts**: Seasonal fluctuations and "false springs" trigger early flowering, leaving crops vulnerable to subsequent frosts.

**Hydrological Instability**: The oscillation between extreme drought and sudden, devastating floods.

**Biological Pressures**: The rapid proliferation of invasive pests and the emergence of new agricultural diseases.

**Nutritional Decline**: Reduced soil fertility leading to lower crop nutrient density. In India, this is a crisis of national importance. Agriculture remains the backbone of the economy, employing nearly 50% of the workforce and contributing approximately 18–20% to the national GDP.

**Anthropogenic Causes of Climate Change:** While natural cycles exist, human-driven development—beginning with the Industrial Revolution—has accelerated the climate crisis. The combustion of fossil fuels has increased atmospheric $CO_2$ by approximately 52% since 1750. Methane levels have similarly surged by over 150%, driven largely by industrial activities and livestock production.

Progress has often come at the cost of our natural carbon sinks. The degradation of the Aravali Range due to mining and urban settlement is a prime example of how we are losing the forests that sequester carbon. Furthermore, global food systems contribute significantly to emissions through deforestation for grazing and nitrous oxide from chemical fertilizers.

**Observable Impacts on Crop Production:** The agricultural sector is witnessing the direct consequences of a 1.1°C to 1.3°C rise in global temperatures. These impacts manifest as unpredictable rainfall and extreme weather events:

**Wheat**: Most varieties require temperatures below 30°C during the grain-filling stages in February and March. Recent heatwaves exceeding this threshold have significantly stunted yields.

**Paddy**: High temperatures in August 2022 were linked to the spread of the Southern Rice Black-Streaked Dwarf Virus across Punjab, Haryana, and Uttarakhand.

Recent Extremes: In late 2025, erratic monsoon rains ruined over 200,000 hectares of standing crops in Punjab alone.

Research indicates that for every 1°C increase above the 25°C threshold, the reproductive phase of many crops shortens by approximately 6%. The IPCC (2023) report confirms that agricultural productivity growth is slowing, particularly in mid to low latitude regions like India.

| Category | Key Metrics / Observation | Impact on Agricultural |
|---|---|---|
| Atmospheric $CO_2$. | ~52% increase since 1750 | Primary driver of global temperature raise and erratic weather. |
| Temperature Rise | 1.1°C to 1.3°C (Global Average) | Shortens crop reproductive phases by ~6% for every 1°C above 25°C. |
| Heat Sensitivity | Threshold of 30°C for Wheat | Temperatures exceeding this during grain-filling significantly stunt yields. |
| Economic Risk | Potential 12% cut in Global GDP | Sustained temperature rise leads to food shortages and socio-economic crises. |
| Crop Loss (India) | 200,000+ hectares (Punjab, 2025) | Result of erratic monsoon rains and extreme weather events. |

**Mitigation and Adaptation Strategies:** To safeguard our future, immediate and collective action is required. We must transition from "greed-based" consumption to "need-based" stewardship.

**Climate-Smart Agriculture (CSA)**: Adoption of heat-tolerant crop varieties and precision irrigation.

**Sustainable Practices:** Shifting toward regenerative farming, integrated pest management, and the use of organic fertilizers.

**Reforestation**: Protecting existing forests and reclaiming degraded lands to restore the local climate balance.

**Education**: Integrating climate literacy into school curricula to foster a generation of environmentally conscious citizens.

## Conclusion

Climate change is an urgent global challenge that poses an unprecedented threat to the health of our agricultural sector. A failure to act risks low production, food shortages, and subsequent socio-economic crises. Recent studies warn that a sustained temperature rise could cut global GDP by up to 12%. As Mahatma Gandhi profound that "Earth provides enough to satisfy every man's needs, but not every man's greed.". So, It is our responsibility to maintain the Earth, ensuring development does not come at the cost of the planet’s life-support systems.

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ISSN : 2583-0910
Agri-India TODAY
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Peer reviewed
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Article ID : 06/VI/44/0626

# DOUBLED HAPLOIDS: A SHORTCUT TO PRECISION BREEDING

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## Abstract

Doubled haploid (DH) technology is widely used in plant breeding for the rapid production of fully homozygous lines within a single generation. Compared with conventional breeding, this approach saves time and improves selection efficiency. Haploids are commonly produced through anther or microspore culture, wide hybridization, and chromosome doubling treatments using chemicals such as colchicine. Because of their genetic stability, DH lines are highly useful in crop improvement, molecular mapping, and genetic research. Although the response varies among genotypes and the technique requires specialized facilities, doubled haploid technology remains an effective tool for accelerating the development of improved crop varieties.

**Keywords:** Homozygosity, anther culture, chromosome doubling

## Introduction

Doubled haploid technology has become an important component of modern crop improvement programs. A doubled haploid plant is produced when the chromosome number of a haploid cell is artificially or spontaneously doubled, resulting in a completely homozygous genotype. Unlike conventional selfing methods that require several generations to achieve homozygosity, DH technology can produce stable lines in a much shorter period. These lines are valuable for breeding, gene mapping, marker-assisted selection, and the development of improved cultivars with desirable traits. In addition, the genetic uniformity of DH populations makes them suitable for molecular and genomic studies.

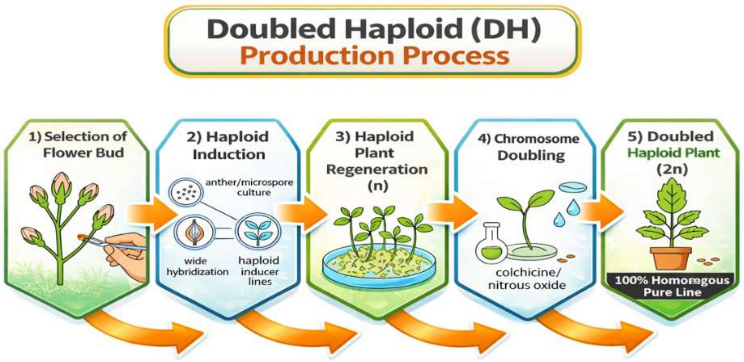

**Fig 1: Process depicting doubled haploid production.**

### Methods of production

1. **Anther/microspore culture** to obtain haploid regenerants, followed by chromosome doubling.
2. **Wide hybridization** with chromosome elimination to obtain haploids, then doubling.
3. **Chemical doubling:** colchicine, oryzalin or other anti-mitotic agents cause chromosome doubling in haploid tissue.
4. **Spontaneous doubling:** sometimes doubling occurs during tissue-culture regeneration.

### Applications of doubled haploids

In plant breeding double haploid can be used in many ways as described below:

### Cultivar development

The development of genetically stable cultivars is one of the major applications of doubled haploid technology. DH lines provide complete homozygosity, allowing breeders to rapidly fix desirable traits and reduce the time needed for variety development. Such lines may be directly released as cultivars or used as parental material in hybrid breeding programs. Several crop species, including barley, wheat, rice, and maize, have successfully utilized DH technology for the production of improved cultivars.

### Mapping quantitative trait loci

Quantitative traits are generally controlled by multiple genes and are strongly influenced by environmental conditions. Doubled haploid populations are highly suitable for QTL analysis because their genetic constitution remains stable over generations. The uniformity of DH lines improves the precision of phenotypic evaluation and supports accurate identification of genomic regions associated with important agronomic traits.

### Haploids in genetics

Disomic inheritance and reduced chromosome number in polyhaploids (e.g., potato dihaploids) make them highly effective for genetic analysis. Their applications include:

- identification of gene number for isozymes using electrophoresis, along with genes governing disease resistance and agronomic traits;
- estimation of heritability for traits such as specific gravity, maturity, glucose content, dormancy, yield, and tuber weight.
- determination of tetraploid genotype through haploid extraction and analysis of proteins, isozymes, and self-incompatibility systems.

### Haploids in evolutionary studies

Comparison of potato dihaploids with diploid wild species has helped clarify the origin of cultivated potatoes. The presence of 2n gametes in both groups suggests that *Andigena*, the ancestor of *Tuberosum*, likely arose multiple times from related diploid populations via sexual polyploidization. Potato haploids have also aided genome analysis through crosses with diploid species, with meiotic studies showing only minor genetic differences. Pachytene chromosome analysis further indicates a close evolutionary relationship between potato and diploid tomato ($2n = 24$).

### Advantages of doubled haploids

- Production of completely homozygous lines within a single generation.
- Considerable reduction in breeding duration compared to repeated selfing.
- Improved efficiency in selection and genetic analysis.

- Useful material for QTL mapping, molecular breeding, and hybrid development.
- Stable and uniform populations suitable for research and cultivar development.

**Disadvantages of doubled haploids**

- Efficiency of haploid induction varies among species and genotypes.
- Tissue culture techniques require skilled personnel and laboratory facilities.
- Regenerated plants may occasionally show abnormalities or reduced fertility.
- Somaclonal variation can arise during in vitro culture procedures.

**Table 1. Varieties developed through double haploid technology.**

| Crop | Method followed | Varieties | Country |
|---|---|---|---|
| Rice | Anther culture | Tanfeng 1, Tan Fong 1, Hua YU 1, Hua 03, Xin Xiu, Xhongua 8, Ta Be 78, Guan 18 | China |
| | Anther culture | Dama | Hungry |
| | Anther culture | Parag 401 (ACR 401) | MH, India |
| | Anther culture | CR Dhan 801 | CRRI, India |
| | Anther culture | Patei and Moccoi | Argentina |
| Wheat | Anther culture | Hua pei 1, Lung Hua 1, Jinghua 1, Yunhua 1, Yunhua 2 | China |
| | Anther culture | Kharoba | Morocco |
| | Anther culture | Florin | France |
| | Wheat x Maize | Glosa, Faur F, Liter, Miranda | Romania |
| Tobacco | Anther culture | Tan Yu 1, Tan Yu 2, Tan Yu 3 | China |
| | Anther culture | F211 (wilt resistant & mild smoking) | Japan |
| Barley | H. bulbosum | Mingo, Gwylan | Canada |

**Table.2: pest and disease resistance lines developed using double haploid technique. (Omesh Kumar and Madhu Choudhary, 2020.)**

| Crop | Line | Resistance to | Reference |
|---|---|---|---|
| Barley | Mingo<br>Q-21681 | Barley yellow mosaic virus<br>Stem rust, leaf rust and PM | Foroughiwer & friedth, 1984<br>Stoffenson *et al.*, 1995 |
| Rice | Zhonghua no-8&9<br>hwasambye<br>Hwachengbyeo<br>Shirayukhine | Blast, high yielding & good quality<br>Leaf blast, BLB & rice stripe tenui virus<br>BPH & cold tolerance<br>BLB & rice tenui virus<br>High yielder, tolerant to major pest and disease | DDBeeong-geum *et al.*, 1997<br>Lee *et al.*, 1989<br>Kazahiro & terahiro (2002) |
| Tobacco | Tan yu 3 | Necrotic strain of potato virus | Witherspoon *et al.*, 1991 |

**Conclusion**

Doubled haploid technology has greatly enhanced the efficiency of plant breeding by enabling rapid development of homozygous lines. The method supports faster cultivar development, precise genetic studies, and effective molecular breeding strategies. Despite certain technical limitations, DH technology continues to play a significant role in crop improvement and modern agricultural research.

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ISSN : 2583-0910
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monthly newsletter

Article ID : 06/VI/45/0626

# AQUACULTURE POTENTIAL OF INDIAN SALMON (*Eleutheronema tetradactylum*)

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## Abstract

Indian salmon, *Eleutheronema tetradactylum*, commonly known as Rawas, is a high-value euryhaline marine fish distributed across the Indo-West Pacific region. The species possesses significant aquaculture potential due to its rapid growth, adaptability to marine and brackish water, and inland saline environments, high fecundity, and strong domestic and export market demand. However, the natural populations are declining due to overfishing, habitat degradation, coastal pollution, and climate change, resulting in their endangered conservation status. This article reviews the biology, distribution, reproductive traits, capture and culture status, diversification potential, and future aquaculture prospects of the Indian salmon. The species exhibits favourable aquaculture characteristics such as tolerance to varying salinity conditions, suitability for coastal and inland saline farming systems, and potential for hatchery-based seed production. Despite these advantages, commercial culture development remains limited because of the absence of standardised breeding and larval rearing protocols, protandrous hermaphroditism, and dependence on wild seed collection. Species diversification in Indian aquaculture is essential to reduce pressure on conventionally cultured species and improve sustainability, and Indian salmon emerges as a promising candidate for this purpose. Future research focusing on broodstock management, captive breeding, hatchery technology, larval nutrition, and selective breeding can support the commercialisation and conservation of this species.

**Keywords:** Indian salmon, *Eleutheronema tetradactylum*, species diversification, mariculture

## Introduction

The marine ray-finned fish species Indian Salmon, also known as Rawas, *Eleutheronema tetradactylum*, belongs to the group of Four-finger threadfins. Endangered due to population decline caused by overfishing, habitat degradation, coastal pollution and climate change, which affects the spawning cycles. Rawas (Marathi), Pozhakkala, Yevakal (Tamil), Norakudiyan, Wahmeen (Malayalam), Maga (Telugu), Sahal (Bengali), Vameenu (Kannada).

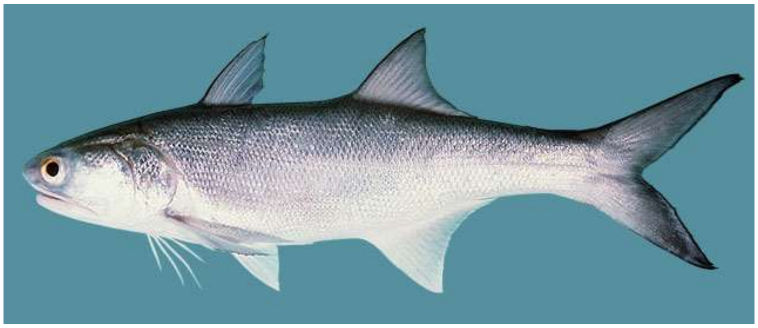

**Fig. 1: Indian salmon**

## Geographical Distribution

*E. tetradactylum* is distributed in the Indo-West Pacific from the Persian Gulf to Papua New Guinea and northern Australia. In India, it occurs along the east and west coasts and supports major fisheries in the Sundarbans on the east coast and in Mumbai and Saurashtra on the west coast.

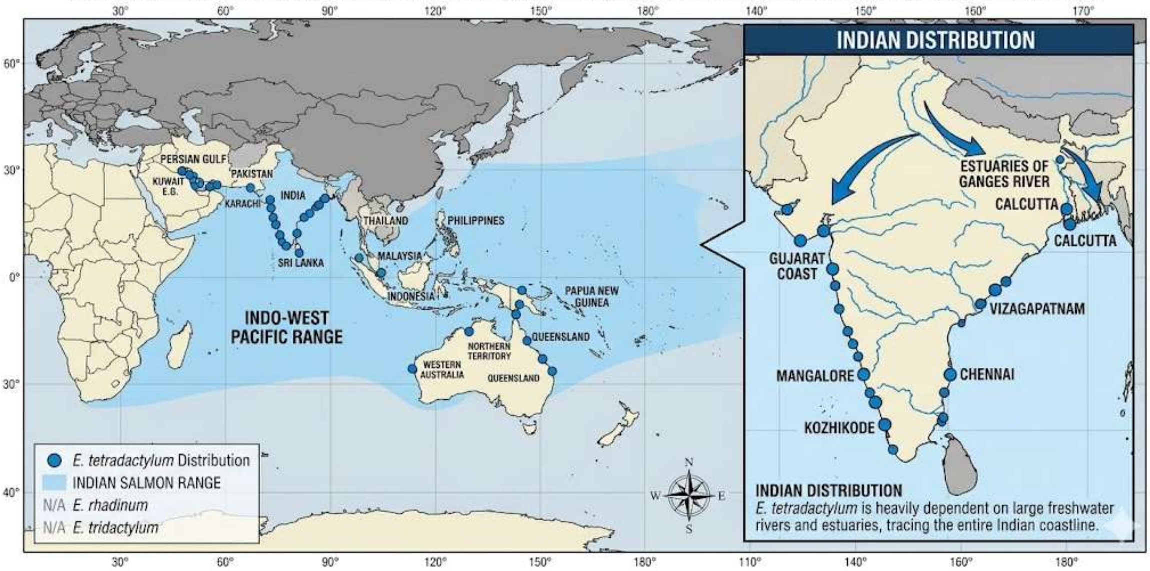
Based on data infographics "Revision of the Indo-West Pacific polynemid fish genus *Eleutheronema* (Teleostei: Perciformes)" (Motomura et al., 2002).

**Fig. 2: World and Indian distribution of Indian Salmon**

## Habitat and Reproductive Biology

It is an Euryhaline species that can thrive in a wide range of salinity and lives in Marine, Brackish, and Freshwater ecosystems. The adult fish migrates for spawning during the peak breeding season (monsoon) from May to September in shallow coastal waters near the continental shelf. Generally, males are small in size and mature early compared to females. The length at first maturity of males is ~24 cm, and females is ~41 cm. Fecundity of the Indian salmon fishes ranges from 1.5 lakhs to 12.5 lakhs/female. They are Multiple spawners, and ovaries are asynchronous in nature. The eggs of this species are pelagic in nature, with oil globules for buoyancy (Hussain *et al*., 2025). The egg diameter listed in the literature is ~400–790 µm, hatching within 12 to 14 hrs of fertilisation. After hatching, larvae (planktonic stage) start to feed on copepods and mysids, and the survival rate depends on the environmental parameters. The early stage of the fish occurs in estuaries, up to the adult stage, after attaining the sub-adult stage starts to migrate to coastal waters and prefers muddy bottoms. The feeding behaviour of the adult fish shifts to Carnivorous and cannibalistic in nature and feeds on small fishes, shrimps, and other crustaceans. They are Protandrous hermaphrodites, in which the fish first mature as males (~20–24 cm TL) and sex reversal to females at (~36–40 cm TL), which is vulnerable to recruitment overfishing adult females as cited in (Hussain et al. 2025).

## Capture and Culture status

In the Indian context, species form a very minor but high-value fishery. Major fishing zones, particularly the West coasts, are the Saurashtra coasts (Maharashtra and Gujarat), while the East coasts, Sundarbans (West Bengal), and Pulicat (Tamil Nadu), are contributing comparatively more. The more commonly used gears for fishing this species are Gill nets (45 – 50 mm mesh), Trawl, and

Bag nets (Vinoth, 2014). In cultural aspects, globally, this Indian salmon culture is under developed state because of the seed production constraints and larval rearing failure. Some of the countries are in culture trials, like Taiwan, Malaysia, and Bangladesh. In India, the culture of Indian salmon is still not commercialised, only at the research and experimental culture level, because of the species potential and species diversification. One of the studies of the Growth performance and survival trials, results are Survival 70 – 80% in culture period of 5 to 6 months from fry to market size at the FCR of ~2.3, which was carried out in brackish water ponds by (Abu Hena *et al*., 2011).

**Major constraints in Culture development**

The breeding and seed production technology is not standardised, the species are asynchronous spawning, which results in a smaller number of seeds being attained, and hatchability variation among the batches. The protandrous hermaphroditic nature also makes broodstock management difficult. In terms of technical difficulties, larval rearing strategy is not standardised, also depends only on wild seed collection. Due to their carnivorous nature, high-protein, high-quality feed requirements increase production costs, and competition with marine capture fishes used as trash fish also affects the sustainability of fisheries.

**Species Diversification**

In the current situation of the world, species diversification is one of the important factors for a sustainable environment. The complete dependence on only a few species will cause overfishing, Stock collapse, Ecological imbalance, and other related impacts. Many regions and countries have undergone overexploitation and habitat degradation with the use of destructive fishing methods, which have resulted in a population decline. By implementing species diversification, the fishing pressure can be distributed across species, which results in reduced stress in stock-specific exploitation. Some of the approaches, like multi-species exploitation, will lower the fishing mortality on single stock, maintaining the trophic balance, which prevents the cascading ecosystem collapse. In aspects of Indian aquaculture, still carp-dominated, which makes inefficient niche utilisation according to (Katiha *et al*., 2005). Some of the studies show that the farm yields only one by third portions of experimental yields, which are studied under the species diversified condition, which is gained by better resource use, such as the water column, feed niches, etc., and other approaches like Polyculture compatibility, which improves the energy transfer efficiency by different feeding habitats in the same environment. Some of the technical reasons for the species diversification are that market fluctuations in a single dominant species, ex, shrimp culture crash due to disease, which poses a high risk of economic loss. By species diversification, the pressure and risk in aquaculture economics, in the fisheries sector, contribute to ~28 million people's livelihoods and enhance the resilience (Ministry of Food Processing Industries, 2024). Some of the other reasons, such as Climate change adaptation, different species adapt to different climate conditions, such as Salinity, Temperature, Dissolved oxygen, and also Indian exports dominated by shrimp and diversification needed for the new export species and value addition of products.

**Potential of *E. tetradactylum* in diversification**

The Indian Salmon, which has high culture potential and species diversification. It is discussed earlier that this species is euryhaline in nature, with a wide range of culture prospects like Fast growth rate (species can reach more than 1m length and average life span ~7 years) and market size potential in the culture trials, which is cited (Abu Hena *et al*., 2011). And also suitable for culture in different culture systems like Coastal ponds, Estuarine farming, Inland saline aquaculture, one of the emerging trends in Indian aquaculture, which is quoted at (Batubara *et al*., 2024). The reproductive performance and fecundity traits of Indian salmon (~12.5 lakhs and multiple spawners) and one of the strong candidates for hatchery development and are also suitable for seed production scaling, are key traits for aquaculture potential. And also, species diversification is important because of the population decline in trend, which is mentioned as the IUCN status of Endangered due to anthropogenic activities, and juveniles are often caught before maturity, which is approximately 250 mm, indicating the recruitment overfishing. If this situation continues, this species will become extinct, so we need to reverse the situation by captive breeding and culture-based methods. The species is considered a high-value table fish with wide domestic and export demand, which has the potential to compete with other coastal aquaculture species, especially shrimps (Hussain *et al*., 2025).

### Seed production and hatchery development

The commercial breeding and seed production technology for this *E. tetradactylum* is not standardised, but some of the countries and research institutes are under experimental units like in Malaysia, where captive breeding has been achieved, but still seed production could not be achieved, and in some other studies reporting that only natural egg collection from wild brooders has been reported. Some of the key constraints are that it is still not possible to standardize seed production technology, and Reproductive complexity, because of protandrous hermaphroditism, makes it difficult to manage brooder sex control, and optimal sex ratios affect fertilization success. Hatchery development is not standardised, because it requires specific environmental parameters (salinity, temperature, photoperiod). Limitations in information on reproductive biology, such as Hormonal protocols, Egg incubation parameters, and larval nutrition models (Hussain *et al*., 2025). In India, institutions such as CIBA and CMFRI are focused on the standardisation of hatchery protocols, commercial seed production units, and reproductive biology.

### Future approach and Aquaculture prospects

From the research studies, we can conclude that *E. tetradactylum* species is an economically high-value, but still underexploited in aquaculture and overexploited in capture fisheries. For the Broodstock development and controlled breeding, ICAR-CIBA and related institutes are on-going approaches to overcome Hormonal manipulation (GnRH analogues, dopamine antagonists), Gonadal histology-guided broodstock conditioning, Controlled Photothermal regimes. In the point of Hatchery & Larval rearing technology, Live feed enrichment of Rotifers, Artemia, Copepods, Micro diet weaning strategies, and Probiotic-mediated gut microbiome stabilisation, some of the other studies suggest using the green water systems and microbial management to improve the larval survival. The adaptation of various culture systems, like for other species, Monoculture (semi-intensive), Polyculture with shrimps, Cage culture on coastal waters for the Grow-out culture system, which is suggested in (Abu Hena *et al*., 2011). For stock enhancement programs, Selective breeding programs, and ranching programs are implemented. Other technical prospects of Indian aquaculture are long coastline, Estuarine ecosystem suitability, and existing mariculture initiatives such as the PMMSY schemes.

### Conclusion

The growing demand for sustainable and diversified aquaculture species highlights the importance of exploring underutilised candidates such as *E. tetradactylum*. Indian salmon possesses several favourable characteristics, including environmental adaptability, high consumer preference, and suitability for multiple farming systems, making it a strong prospect for future aquaculture expansion. However, successful commercialisation depends on overcoming critical bottlenecks related to seed production, larval survival, broodstock management, and feed development.

Conservation-oriented aquaculture approaches, combined with advances in hatchery technology and culture practices, can simultaneously reduce fishing pressure on wild stocks and improve production sustainability. With continued research support, policy interventions, and farmer adoption, Indian salmon can contribute significantly toward species diversification, livelihood enhancement, and resilient aquaculture development in India.

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ISSN : 2583-0910
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Article ID : 06/VI/46/0626

# HYBRID PIGEONPEA: PROMISE YET TO REACH EVERY FARMER

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## Abstract

Pigeonpea hybrid technology has emerged as a promising approach to overcome the long-standing problem of low productivity in pigeonpea cultivation. The development of genetic male sterility and cytoplasmic-genic male sterility systems enabled the release of several high-yielding hybrids with significant yield advantages over conventional varieties. Despite these scientific achievements, large-scale farmer adoption remains limited due to challenges in seed production, genetic purity maintenance, limited cytoplasmic diversity, low seed multiplication ratio, and inadequate institutional support. Recent advances in genomics, molecular markers, and breeding strategies offer new opportunities to improve hybrid development and seed systems. Strengthening research, policy support and farmer awareness will be crucial for realizing the full potential of hybrid pigeonpea.

**Keywords:** Pigeonpea, Hybrid, Heterosis, Male sterility, Fertility restoration

## Introduction

Pigeonpea (*Cajanus cajan* (L.) Millspaugh) is an important protein-rich legume crop contributing to food and nutritional security in tropical and subtropical regions. Early pigeonpea breeding mainly focused on developing superior pureline varieties with improved yield, adaptability, and disease resistance. However, limited yield improvement through conventional breeding led researchers to explore hybrid technology using cytoplasmic-genic male sterility (CGMS) systems. Since the initiation of hybrid breeding programs at International Crops Research Institute for the Semi-Arid Tropics in the 1970s, several promising hybrids showing 30–50% higher yield than conventional varieties have been developed. Despite these scientific advances, large-scale farmer adoption remains limited due to challenges related to genetics, seed production, and institutional support.

**Evolution of hybrid breeding**

Pigeonpea breeding entered a new era in the early 1970s when male sterile lines were first identified, paving the way for hybrid development. The first genetic male sterility (GMS)-based hybrid, ICPH 8, was developed in 1991, followed by others like PPH 4, CoPH 1, and AKPH 4101. However, GMS-based systems were soon found impractical for large-scale seed production because of their dependence on manual pollination.

A turning point came with the discovery of cytoplasmic-genic male sterility (CGMS) around 2000. The first CMS-based hybrid, GTH 1, was released in 2006. Later, hybrids such as ICPH 2671 and ICPH 2740 demonstrated 30–50% yield advantages with comparable maturity and disease resistance. These successes established that hybrid pigeonpea technology works - scientifically and agronomically. But scaling it up to farmers has proved far more complex. Despite its proven potential, several barriers continue to limit the widespread success of hybrid pigeonpea.

**Barriers to Hybrid Pigeonpea success**

**1. Complex and costly seed production**

Unlike cereals such as maize or rice, pigeonpea is partially cross-pollinated (entomophilous) - it depends heavily on insects for pollen transfer. This makes controlled hybrid seed production difficult.

- The female (A-line) must be male sterile, while the male (R-line) must effectively restore fertility in the hybrid. Maintaining these parental lines (A, B, R) demands skill, resources, and isolation facilities.
- The required isolation distance is larger than for self-pollinated crops, as pollinating insects like bees can carry pollen over long distances.
- Seed producers also face issues of genetic contamination due to incomplete isolation or variation in insect behavior under different climatic conditions.

Consequently, the cost of hybrid seed is high, and many private companies are reluctant to invest in its production without guaranteed demand or strict quality control systems.

**2. Problems of Genetic Purity and Quality Control**

For hybrids to perform well, the genetic purity of the seed must exceed 95%. Traditionally, this is verified using a Grow-Out Test (GoT) - planting a sample of seed and checking its progeny for distinguishing traits. But pigeonpea's photoperiod sensitivity prevents GoT from being used effectively. As it flowers only under 10-11-hour days, seeds harvested in one season cannot be tested immediately in the next under long summer days. This means that quality testing is delayed or infeasible for many released hybrids. Researchers have proposed molecular marker-based testing kits as an alternative faster and more reliable - but these are still limited in availability and adoption among seed producers (Saxena *et al*., 2025).

**3. Limited Cytoplasmic Diversity in CMS Lines**

The success of hybrid breeding depends on diverse sources of cytoplasmic male sterility (CMS). However, the majority of CMS lines in pigeonpea are derived from a single cytoplasmic source, known as $A_4$ cytoplasm from *Cajanus cajanifolius*. This has led to concerns about uniformity and vulnerability. Lack of cytoplasmic diversity increases the risk of environmental instability in fertility restoration - hybrids carrying only one dominant restorer gene may fail to restore fertility fully under certain conditions. Studies have shown that stability requires both dominant restorer genes to be present (Saxena *et al.*, 2015). From a breeding perspective, developing CMS systems from other Cajanus species (like *C. scarabaeoides*) is essential for long-term stability and sustainability.

**4. Low Seed Multiplication Ratios**

Even when hybrid seed is successfully produced, the seed multiplication ratio is low — typically 1:50 to 1:100 - compared to cereals where it can exceed 1:200. This makes hybrid pigeonpea seed expensive and scarce. Farmers often re-use their seed, which further erodes hybrid purity in subsequent generations. Without an efficient seed production network or buy-back mechanism, private seed companies are hesitant to expand their operations.

**5. Limited Awareness and Institutional Support**

Hybrid pigeonpea is a relatively new technology. Many farmers and seed companies remain unaware of its economic advantages or technical requirements. There are also no national seed standards prescribed specifically for pigeonpea hybrids (Saxena *et al.*, 2015). Field demonstrations and farmer-participatory trials in states like Madhya Pradesh and Odisha showed encouraging yield results, but inconsistent seed supply and lack of organized seed certification remain major bottlenecks.

**6. Breeding Constraints: The Core Scientific Challenges**

- Long generation time: Pigeonpea is a long-duration crop (4–6 months), slowing breeding cycles compared to cereals like rice or wheat.
- Limited genetic diversity in cultivated germplasm reduces the potential to select heterotic parental combinations.
- Complex inheritance of fertility restoration makes it difficult to identify stable restorer lines.
- High genotype × environment (G × E) interaction affects fertility restoration and yield stability.
- Lack of reliable heterotic group classification across regions hampers the breeding of location-specific hybrids.

These challenges collectively make hybrid pigeonpea breeding more resource- and time-intensive than typical crop hybridization programs (Saxena *et al.*, 2015).

**Future Integration**

Despite the challenges, breeders and scientists remain optimistic. The integration of genomics tools with traditional breeding methods is now revolutionizing hybrid pigeonpea research. Genomic-assisted selection (GAS) and marker-assisted backcrossing (MABC) are helping breeders identify fertile and stable restorer lines more efficiently, Molecular markers and DNA fingerprinting are now being used for seed purity testing and parental line identification, Efforts are underway to diversify cytoplasmic sources and create improved male-sterile lines adapted to different agro-ecologies, Research is also focusing on short-duration hybrids and disease-resistant lines that can fit into multiple cropping systems. Furthermore, collaboration among ICAR institutes, ICRISAT, and state agricultural universities has strengthened national breeding programs and field testing networks (Singh *et al.*, 2024).

**Looking Ahead: From Lab to Farm**

Hybrid pigeonpea offers a clear technological edge to boost pulse production and farmers' incomes - but unlocking its potential depends on bridging the seed production and dissemination gaps.
Key priorities for the coming decade include:

1. Developing stable, diverse parental lines with broad adaptability.
2. Establishing quality control standards and marker-based purity testing protocols.
3. Building public–private partnerships for seed multiplication and promotion.
4. Training farmers and seed producers in hybrid technology.
5. Investing in policy support to make hybrid seed affordable and available.

With concerted efforts, hybrid pigeon pea can become a cornerstone of India's pulse revolution - turning a promising research success into a sustainable farming reality.

## Conclusion

Hybrid pigeonpea represents a major scientific advancement with the potential to enhance pulse productivity and farmer income. However, several breeding, seed production, and dissemination challenges continue to restrict its wider adoption. Integrating genomics-assisted breeding, improved seed systems, and stronger institutional support can accelerate its success. With sustained research and coordinated efforts, hybrid pigeonpea can play an important role in future pulse security and sustainable agriculture.

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ISSN : 2583-0910
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Peer reviewed
monthly newsletter

Article ID : 06/VI/47/0626

# DENDROLOGICAL, PHYTOCHEMICAL, AND ETHNOBOTANICAL PROFILE OF *Heterophragma quadriloculare* (Roxb.) K. Schum

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## Abstarct

*Heterophragma quadriloculare* (Bignoniaceae), commonly known as *Waras*, is a tree specialized for the seasonally dry tropical biomes of the Indian subcontinent. This article synthesizes its taxonomic framework, morphological adaptations, phytochemistry, and ecological utility. To survive dry conditions, the species possesses water-retaining cortical mucilage, touch-sensitive stigmas optimized for nocturnal *Xylocopa tenuiscapa* pollination, and a specialized four-celled capsule for wind dispersal. Pharmacological studies validate its traditional medicinal uses, notably confirming that foliar ursolic acid (0.93% w/w) drives anti-diabetic activity through insulin-receptor regulation. Beyond its therapeutic value, the tree provides high-density, warp-resistant timber for rural architecture, serves as a vital dry-season forage source for wildlife, and acts as an efficient carbon sink with a sequestration potential of 15.22 tons per individual. *H. quadriloculare* thus represents a critical resource for biodiscovery, environmental management, and ecological conservation.

## Introduction

The botanical landscape of the Indian subcontinent is characterized by a high degree of evolutionary specialization among its deciduous flora, particularly within the seasonally dry tropical biomes that define the central and southern regions of the peninsula. Within these specialized ecosystems, *Heterophragma quadriloculare* (Roxb.) K. Schum., a prominent arboreal member of the family Bignoniaceae, represents a significant subject of study. The species is notable for its specialized reproductive strategies, complex secondary metabolite profile, and historical utility in traditional ethnomedicine and rural structural engineering. Colloquially designated as *Waras* or *Varas* within the Marathi and Gujarati-speaking zones of the Western Ghats, this taxon highlights the intersection of botanical complexity and ethnobotanical importance.

## Taxonomic Evolution and Nomenclatural

The systematic classification of *Heterophragma quadriloculare* has undergone various refinements since its initial documentation in the late 18th century. The species was first identified and described by the pioneering botanist William Roxburgh as *Bignonia quadrilocularis* in his seminal 1799 publication, *Plants of the Coast of Coromandel*. The specific epithet, *quadriloculare*, is a direct reference to the internal morphology of the fruit capsule, derived from the Latin roots *quadri-* (four) and *loculus* (compartment), identifying the four-celled architecture of the mature pod. In 1825, Sprengel reassigned the species to the genus *Spathodea*, resulting in the synonym *Spathodea roxburghii*, which was subsequently followed by De Candolle's 1845 classification as *Heterophragma roxburghii*. The currently accepted nomenclature was established in 1895 by Karl Moritz Schumann, who transferred the species to the genus *Heterophragma* in Engler and Prantl's *Die Natürlichen Pflanzenfamilien*. This genus name itself is evocative of the plant's structural characteristics, stemming from the Greek *hetero* (different) and *phragma* (fence), emphasizing the unique compartmentalization of its reproductive structures.

**Taxonomic Hierarchy**

| **Taxonomic Rank** | **Scientific Designation** |
|---|---|
| **Kingdom** | Plantae |
| **Phylum** | Angiosperms |
| **Class** | Eudicots |
| **Order** | Lamiales |
| **Family** | Bignoniaceae |
| **Genus** | *Heterophragma* |
| **Species** | *Heterophragma quadriloculare* (Roxb.) K. Schum. |

Across the diverse linguistic landscape of India, *Heterophragma quadriloculare* is recognized by a variety of regional names that reflect its integration into local culture and traditional practice.

**Vernacular Nomenclature**

| **Language** | **Vernacular Name(s)** |
|---|---|
| **Marathi** | Waras, Murus, Panlag, Varas |
| **Hindi** | Warras, Pullung, Pullnug |
| **Telugu** | Kapu-gargu, Kala-goru, Baray-kalikod, Bondugu, Koligottu, Barukoli-gottu |
| **Kannada** | Bechadi mara, Kaligottu mara, Adavi nugge |
| **Tamil** | Bara-kalagoru |

### Morphological Architecture and Vegetative Development

*Heterophragma quadriloculare* presents as a large macro-phanerophyte, typically attaining a vegetative height ranging from 5 to 15 meters, with exceptional specimens reaching greater heights in favorable ecological niches. The structural integrity of the tree is defined by an erect, lignified stem characterized by a robust, rough brown periderm that exhibits occasional exfoliation. A significant diagnostic physiological feature of the stem is the presence of internal mucilage within the cortical and medullary tissues, which functions as a hydrological buffer to contribute to the tree's physiological resilience in seasonally arid environments. The foliar arrangement of the species is complex, consisting of simply pinnate, imparipinnate leaves that measure between 30 and 60 cm in length. These compound leaves are crowded near the terminal ends of the branches, providing a dense canopy during the growing season. Each leaf comprises 3 to 5 pairs of opposite leaflets and a single terminal leaflet. Individual leaflets are elliptic-oblong, measuring up to several centimeters in length, and are distinctive for their unequal-sided or oblique bases. In specific phenological stages, particularly during juvenile growth or under osmotic stress, the leaflets exhibit a soft, velvety (tomentose) trichome layer, which serves as a critical field identification marker.

### Reproductive Morphology and Phenology

The reproductive morphology is characterized by terminal panicles that are many-flowered and densely tomentose. The flowers are relatively large, reaching 5 to 6 cm in length, and are supported by an irregularly lobed, densely hairy calyx. The corolla is tubular-ventricose, typically exhibiting a white color with a distinct rosy or pinkish tinge, particularly at the crinkled or crisped margins. The internal floral structure includes four didynamous stamens with filaments that are hairy at the base, and an elongated style terminating in a bilobed stigma.

A unique floral characteristic is the touch-sensitive stigma, which closes rapidly upon contact by a pollinator to optimize pollen deposition. The species relies on a specialized nocturnal pollination system serviced primarily by the large carpenter bee, *Xylocopa tenuiscapa*. Upon successful fertilization, the tree produces an elongated, straight, woody capsule that serves as the primary fruit. This capsule, measuring 20 to 30 cm in length, is four-celled (quadrilocular) and contains numerous flat, winged seeds designed for anemochory (wind dispersal). The presence of these winged seeds within a compartmentalized capsule is a definitive trait of the genus and underpins the tree's reproductive success in the open, windy environments of dry deciduous forests. Flowering and fruiting typically occur between December and April, peaking in February, with the tree uniquely remaining leafy even while in bloom.

### Phytochemical Constitution and Ethnopharmacological Applications

*Heterophragma quadriloculare* is highly valued in traditional Indian medicine for its diverse therapeutic applications, many of which have been validated through modern phytochemical and pharmacological profiling. The tree’s medicinal efficacy is attributed to a complex profile of secondary metabolites, including alkaloids, flavonoids, tannins, phenolics, and terpenoids (such as lupeol) localized within the foliar and cortical tissues.

### Bioactive Anti-Diabetic Mechanism

Foliar extracts exhibit marked anti-diabetic properties, which are scientifically validated by the quantification of ursolic acid (0.93% w/w) within the leaves. Ursolic acid acts as a bioactive agent that stimulates glucose uptake via the up-regulation and structural modulation of insulin receptors, matching its historical use in oral ethnomedicinal preparations for diabetes management.

The species serves multiple ethnopharmacological roles through targeted local preparations:

- **Dermatological and Antifungal Action:** The leaves serve as a primary remedy for various skin conditions, including chronic sores, toe sores, and chilblains. For the treatment of tinea pedis (athlete's foot), freshly prepared leaf juice (*swarasa*) or a leaf paste (*kalka*) is applied topically to the affected area once or twice daily for a 2–3 day duration. Its antiseptic, antibacterial, and antifungal actions facilitate rapid wound healing and prevent secondary infections.
- **Systemic and Internal Treatment:** Preparations derived from the bark and roots are traditionally utilized to treat dysentery via internal administration. Additionally, these extractions have found utility in folk practices as a historical antidote for snakebites.
- **Ethnoveterinary Medicine:** In specific tribal areas, the stem bark is soaked in water overnight to produce a cold infusion. This preparation is administered orally to livestock showing signs of systemic illness or anorexia to stimulate appetite and recovery.

### Socio-Economic Utility and Ecological Roles

Beyond its pharmacological value, *Heterophragma quadriloculare* plays an important role in rural economics, traditional material culture, and ecosystem dynamics.

### Utility of wood

The wood of *Heterophragma quadriloculare* is dense, durable, and exhibits excellent seasoning properties, making it a vital resource for rural architecture and domestic manufacturing.

- **Structural Framing:** In regions such as the Koyna Valley of Maharashtra, the timber is preferred for fabricating door-frames due to its dimensional stability and resistance to warping under fluctuating humidity cycles. It is also employed for building frames, structural poles, and planks in rural dwellings.

- **Agricultural Implements:** Because of its high mechanical resistance to wear, the wood is utilized as a primary material for manufacturing agricultural tools, tool handles, and small domestic implements.

**Ecological Contributions**

- **Trophic Resource:** The tree serves as a critical food plant for the Hanuman Langur (*Semnopithecus entellus*) in the Western Ghats, providing foliar and floral nutrients during the dry season when alternative forage is limited.
- **Biomimetic and Pollinator Support:** Its specialized nocturnal flowering phenology provides a reliable and continuous energetic resource for its primary pollinator, *Xylocopa tenuiscapa*.
- **Nutritional Supplementation:** The tender leaves are traditionally harvested and consumed as a supplemental vegetable resource by local human communities.
- **Carbon Sequestration:** In environmental management and climate mitigation frameworks, *Heterophragma quadriloculare* has been identified as a significant sink for atmospheric carbon. Quantitative research has recorded a carbon sequestration potential of **15.22 tons** per individual tree, emphasizing its value in regional reforestation and carbon offset initiatives.

*Heterophragma quadriloculare* presents a compelling evolutionary synthesis of morphological specialization, chemical defense, and ecological utility within the seasonally dry tropical biomes of the Indian subcontinent. Its internal hydrological adaptations, such as cortical mucilage, alongside its distinct four-celled capsule designed for anemochory, illustrate a highly refined evolutionary response to severe osmotic and seasonal stress.

Furthermore, empirical validations of its ethnopharmacological profile—most notably the isolation of ursolic acid for insulin-receptor regulation—substantiate the traditional wisdom of indigenous medical practices. When integrated with its high-density, warp-resistant timber properties and its measured carbon sequestration capacity of 15.22 tons per tree, *Heterophragma quadriloculare* emerges not merely as a subject of regional taxonomic interest, but as a critical macromolecular and structural asset for ecological conservation, sustainable forestry, and biodiscovery initiatives in tropical dry forest ecosystems.

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ISSN : 2583-0910
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Article ID : 06/VI/48/0626

# *Tremella fuciformis*: BIOLOGY, CULTIVATION AND THERAPEUTIC SIGNIFICANCE

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## Introduction

More than 100 species of *Tremella* have been reported worldwide. Among them, *Tremella fuciformis* is one of the most well-known and cultivable species. It belongs to the family Tremellaceae under the phylum Basidiomycota and order Tremellales. *Tremella fuciformis* is commonly known as snow fungus, snow ear fungus, silver ear fungus, or white jelly mushroom, while in China it is commonly referred to as "Yiner" or "Baimuer." It is widely valued for its nutritional benefits and health-promoting properties and has been traditionally used for health promotion and longevity in China and other East Asian countries for many years.

## Habitat and Ecology

*Tremella fuciformis* is an obligate fungal parasite that specifically associates with fungi belonging to the genera *Annulohypoxylon* (such as *Annulohypoxylon archeri*) and *Xylaria*. Unlike many other edible mushrooms, it cannot grow and complete its life cycle independently. Rather than growing directly on wood, it develops on the mycelium of these host fungi, which themselves function as decomposers of dead hardwood. This highly specialized interaction makes the occurrence of *T. fuciformis* an indirect indicator of the presence of its host fungi. The mycelium of *T. fuciformis* establishes close contact with the host mycelium and acquires nutrients from it while maintaining the host alive for sustained growth.

## Morphological Characteristics

*Tremella fuciformis* is characterized by a gelatinous, translucent fruiting body that is typically snow-white to slightly amber in colour, resembling a delicate snowflake or coral-like flower. The basidiocarp consists of irregular, thin, and highly contorted lobes arranged in clustered formations, generally measuring 3–10 cm in diameter, although larger specimens may develop under favourable growth conditions. Its texture is soft, elastic, and gelatinous when adequately hydrated. Under dry conditions, however, the fruiting body becomes horny and brittle, but readily regains its original form upon rehydration. This reversible characteristic is a common adaptive feature of gelatinous fungi, enabling survival during unfavourable environmental conditions.

## Nutritional and Therapeutic Value of *Tremella fuciformis*

*Tremella fuciformis*, recognized as a valuable source for functional foods, nutraceuticals, and pharmaceutical applications, contains a wide range of nutritionally important and biologically active compounds, including proteins, fatty acids, polysaccharides, enzymes, phenolic compounds, flavonoids, dietary fibre, and trace elements. Among these, *Tremella fuciformis* polysaccharides (TFPS) are considered the major bioactive constituents and are widely distributed in the fruiting body, spores, mycelium, and fermentation broth. These polysaccharides exhibit several health-promoting properties, including immunomodulatory, antioxidant, antitumor, anti-aging, hypoglycaemic, hypolipidemic, and neuroprotective activities.

### Life Cycle

*Tremella fuciformis* exhibits a dimorphic life cycle characterized by two distinct developmental forms: a unicellular yeast-like phase and a filamentous hyphal phase. The life cycle begins with the germination of haploid basidiospores, which reproduce through budding and establish a yeast-like stage. Under favorable conditions, compatible yeast cells undergo conjugation, resulting in the formation of dikaryotic hyphae. The filamentous phase subsequently interacts with its host fungus and develops into mature fruiting bodies (basidiocarps).

### Cultivation

Commercial cultivation of *Tremella fuciformis* was first successfully achieved on synthetic logs in Fujian Province, China, in 1978. Following are the steps:

1. Mixed Mother Culture Preparation: *Tremella fuciformis* is cultured on agar slants and incubated at 25°C. When the colony reaches approximately 1 cm diameter, a small amount of *Hypoxylon archeri* is introduced at a ratio of 1000:1 (*T. fuciformis*: *H. acheri*) to establish a stable mixed culture system used for primary spawn production.
2. Primary Spawn Production: The mixed mother culture is inoculated into supplemented sawdust–bran substrate with approximately 65% moisture content and incubated at 25°C. Small primordia resembling half a grain of rice indicate successful establishment of both fungi.
3. Spawn Production: Primary spawn is selected based on vigorous primordia formation, deep *Tremella* mycelial penetration, and robust feather-like growth of *H. acheri*. Primordia are removed and the substrate moisture is maintained at 65–70%. Spawn is incubated at 26°C for 18–22 days. The appearance of white mycelial globules indicates spawn maturity, and it becomes ready for use 2–3 days after globule formation. One spawn bottle is generally sufficient for approximately 20 synthetic logs.
4. Spawning (Inoculation): Only the top 3 cm of mixed spawn is used for inoculation. Synthetic bags (12 × 60 cm) with four inoculation holes (1.5 cm diameter and 1.2–1.5 cm depth) are prepared and sealed after inoculation using adhesive tape or microfilter bags.
5. Spawn Run and Fruiting Body Development: Inoculated bags are incubated at 25–28°C for 3–5 days to promote *Hypoxylon* growth, followed by 23–25°C with increased aeration to support *Tremella* mycelial development. After 10–15 days, bags are transferred to the fruiting room. Formation of white mycelial globules with yellowish exudates indicates primordia initiation; excess exudates should be drained. Primordia develop within 15–20 days, and mature fruiting bodies are harvested 35–40 days after spawning, with the possibility of a second flush under favourable conditions.

### Economic Importance and Market Potential

*Tremella fuciformis* has considerable commercial importance due to increasing demand for functional foods, nutraceuticals, cosmetic products, and medicinal formulations. It is extensively cultivated in China and East Asian countries and is gaining popularity worldwide because of its bioactive polysaccharides and health benefits.

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ISSN : 2583-0910
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Article ID : 06/VI/49/0626

# AUTOMATED DRONE SPRAYING: THE FUTURE OF AGRICULTURAL PEST MANAGEMENT

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## Abstract

This in-depth research into how automated drone spraying technology is reshaping the face of modern agriculture so much that its advantages over traditional manual spraying methods have been proven beyond any doubt. Currently, the worldwide agricultural drone market is estimated to be worth $4.98 billion and expected to rise to $18.22 billion by the year 2030, which is a clear indication of the industry's acknowledgment of this major change. On one hand, drone spraying can cover 40-70 acres per hour, which is 70% faster than manual methods, and on the other hand, it also reduces chemical usage by 25-40% and cuts down operational labour costs by 90%. It is a win-win situation for the environment as well: drones use 2.43 times less energy, give off 70% fewer carbon emissions, do not cause soil compaction, and help save water by 94%. Finding a balance between economics and ecology, drone spraying automation is the key for modern agriculture that wants to stay competitive as it not only contributes to sustainability but also ensures that farmers and workers profit and stay safe. With investment recovery happening in just 1-3 years, and 15% on average for yield increases, the future is bright for automated drone spraying.

**Keywords*:*** Automated drone spraying, UAVs, precision agriculture, pest management, efficiency comparison, cost-effectiveness

## Introduction

The global agriculture drone market is set to grow from about $4.98 billion in 2023 to $18.22 billion by 2030—an impressive 20.3% compound annual growth rate (CAGR). This explosive growth reflects the increasing recognition of drone spraying technology as a transformative solution for modern agriculture. Agricultural spraying drones in 2025–2026 are no longer limited to basic aerial spraying, with the latest generation engineered with advanced features for precise application including high-precision GPS navigation, integration of multispectral sensors for crop health analysis, and AI-powered analytics to determine optimal spraying patterns. The shift from manual to automated spraying systems is driven by the need for greater efficiency, reduced operational costs, and heightened environmental consciousness. This article explores these dimensions in detail, providing farmers and agricultural professionals with evidence-based insights to inform their adoption decisions.

## Automated Drone Spraying: Technology & Recent Developments

Automated drone spraying means flying a type of drone (UAV) that has a precise crop spraying system on it over the crops to apply pesticides, herbicides, and fertilizers. These systems have smart tanks and nozzles for spraying that can be customized, platforms that are light yet strong so that the payload and flight times are maximized, and volume and frequency controls that can be done automatically after live observations have been made.

1. **Advanced Autonomous Systems:** By joining forces, DroneDash Technologies and GEODNET established GEODASH Aerosystems that created a farming spraying drone that can be used inside geo-fenced boundaries without relying on pre-mapped fields and capable of in-flight perception and centimetre-level positioning. This unit integrated DroneDash's AI vision with GEODNET's position correction so the aircraft could recognize rows, trees, and terrain while flying. Pilots and validation projects are expected to run through 2025 and early 2026 before a commercial release in Q3 2026.
2. **Next-Generation Models:** Hylio is in the phase of developing and flight testing the HYL-150 ARES, its most recent spraying drone which is planned for launch in the first quarter of 2026. This drone has the weight of 141 lbs and the company considers it as the major project. Alongside the drone there will be a 10 lbs. "scout drone" called the Photon that is expected to be made available in the 2025 fourth quarter.
3. **AI-Driven Precision:** Drone spraying operations that are cost-effective in 2026 will probably rely on utilizing satellite data in real-time along with NDVI crop monitoring for directing every spray mission precisely. Besides, AI algorithms and IoT sensors will be used for planning UAV flights at times when results are optimal and risks are minimal.

**Efficiency Comparison: Drone Spraying Vs. Manual Spraying**

1. **Drone Spraying:** Expert estimates indicate that by 2025 drone spraying systems will be able to cover up to 40 acres per hour, which means that they will be 70% more effective than traditional methods. In fact, drones get their job done just in 1 hour time and around 70 acres (more than 28 hectares) can be sprayed. Besides that, their spraying speed can be compared with other tasks as well, for example, they are 5 times faster than manually applying greenhouse shading and even 7 times faster in cleaning solar panels.
2. **Manual Spraying:** The spraying manually of pesticides is a work that is carried out at fairly low speeds and can easily be affected by changes in weather, different types of terrain, and other environmental factors. Besides that, one person can only cover a small part of what a drone can do in the same period of time.
3. **Efficiency Metrics:** For example, a drone usually weighs 20 kilograms as its maximum payload, and it can perform spraying work of the area equalling 10 acres in around 5 minutes. In the instance of a great-sized farm, for example, 100 acres of farmland, the drones will be capable of finishing spraying within the hour.
4. **Work Efficiency:** UAVs achieved a working efficiency of 4.11 ha/h, 1.7 to 20 times higher than other methods, with UAVs achieving a control efficacy of 70.9% on wheat aphids, comparable to other sprayers.
5. **Precision & Effectiveness:** Drone spraying makes it possible to apply the treatment only to specific portions of a field, which lowers the input costs as the crops are treated chemically with exactly the amount required thus minimizing the overuse and waste.

| Factor | Manual Spraying | Drone Spraying |
|---|---|---|
| Speed | 5-10 acres/day | 40-70 acres/hour |
| Labor Required | 5-10 workers | 1 operator |
| Chemical Usage | 100% baseline | 60-75% |
| Cost per Acre | Higher (manual labor) | 25-40% reduction |
| ROI Timeline | N/A | 1-3 years |
| Energy Consumption | 365.3 MJ/ha | 146.8 MJ/ha |
| Carbon Emissions | 41.3 kg $CO_2$/ha | 14.5 kg $CO_2$/ha |
| Soil Compaction | Significant | Eliminated |
| Operator Safety | Higher chemical exposure | Minimal exposure |
| Precision | Lower | High (AI-guided) |
| Weather Adaptability | Limited | Light winds acceptable |

## Challenges & Considerations

Drone spraying, although a clear winner, still faces certain restrictions:

- **Payload Capacity:** Smaller payloads mean that for large operations there would be a need for more frequent refilling
- **Battery Management:** Charging facilities and flight time limitations
- **Initial Investment:** The upfront costs, however, are greatly balanced by a fast Return on Investment
- **Regulatory Framework:** Rules governing drone operations are still being developed
- **Weather Limitations:** Incapable of working under strong wind or heavy rain

## Conclusion

Available data clearly indicate that automated drone spraying outperforms manual spraying by a large margin in terms of efficiency, cost-effectiveness, and environmental impact. Operating livestock with drones, which is 70 % more efficient, can allow for 25-40 % less chemical usage, 90% labour cost savings, and much less carbon emissions, thereby serving as a revolutionary technology for the modern agriculture.

Modern agriculture is indeed moving toward sustainability and precision, and the economic benefits of using drones only add to this. Given the increasing labour costs and tightening environmental regulations, the move from manual to drone-based spraying is considered by many as more than just a mere option, the right path for competitiveness and ecological responsibility.

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ISSN : 2583-0910
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Article ID : 06/VI/50/0626

# NANOPARTICLES MEDIATED GENE DELIVERY IN PLANTS

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## Abstract

The increasing global population and the growing impact of climate change are major threats to food security. Plant genetic engineering has emerged as an important strategy for developing crops with improved stress tolerance, nutrient uptake, yield and nutritional quality. Various methods are available for introducing exogenous genetic material into plants. Among these, Agrobacterium-mediated transformation (AMT) has been widely used for plant genome manipulation. However, it is often limited by species specificity and the potential for tissue damage. In this context, nanoparticle-mediated gene delivery has gained attention as an effective alternative to the AMT. Nanoparticles can passively penetrate plant cell walls and efficiently deliver biomolecules to plant tissues with minimal damage. Moreover, this approach is applicable to a wide range of plant species, including those that are resistant to AMT.

**Keywords**: Agrobacterium mediated transformation (AMT), Genetic engineering, Nanoparticles,

## Introduction

The increasing global population and climate change are major threats to food security. Plant genetic engineering plays an important role in developing crops with improved yield, nutritional quality, herbicide resistance, and tolerance to biotic and abiotic stresses. Several methods have been used to introduce exogenous genetic material into plants, including Agrobacterium-mediated transformation (AMT), biolistic delivery, electroporation, and protoplast transfection (Kant and Dasgupta, 2017). However, its application is restricted by species dependency, narrow host range, and lengthy tissue culture procedures (Sabbadini *et al*., 2019). To overcome these limitations, nanoparticle -mediated gene delivery has emerged as a promising alternative in plant biotechnology. Nanoparticles can efficiently transport biomolecules across the plant cell wall with minimal tissue damage and without requiring external forces. Their ability to deliver DNA, RNA, and other cargoes into a wide range of plant species, including those recalcitrant to AMT, makes them valuable tools for modern plant genetic engineering and sustainable crop improvement.

## Types of Nanoparticles Used in Plants

Nanoparticles (NPs) are ultrafine particles smaller than 100 nm that can be engineered to deliver biomolecules, such as proteins, drugs, and nucleic acids, into cells (Yin *et al*., 2017). In plant biotechnology, nanoparticle-mediated gene delivery has emerged as a promising approach for introducing desirable traits related to crop yield and stress tolerance (Yong *et al*., 2024). Nanoparticles can bypass the plant cell wall through charge-based interactions and passive diffusion, enabling efficient transient and stable transformations with minimal tissue damage (Lv *et al.*, 2020). Unlike conventional methods, nanoparticle-mediated delivery is non- invasive and applicable to a wide range of plant species, including those resistant to Agrobacterium-mediated transformation (AMT). In addition, nanoparticles have low toxicity and high potential for future plant biotechnology applications (Hamers, 2017). Various nanocarriers used for gene delivery include carbon-based, metallic, and silicon-based nanoparticles, as well as bio-inspired carriers such as liposomes and vesicles Carbon dots (CDs).

Carbon dots (CDs) are carbon-based nanoparticles with diameters of less than 10 nm. Based on their chemical composition, they are classified into graphene quantum dots (GQDs), carbon nanodots (CNDs), and polymer dots (PDs), whereas CNDs are further divided into carbon nanoparticles (CNPs) and carbon quantum dots (CQDs) (Lopes *et al.*, 2022). Owing to their small size and high tensile strength, CDs are widely used as nanocarriers for gene delivery in plants. Their surface can be functionalized with positively charged polymers, enabling the efficient binding and delivery of negatively charged nucleic acids into intact plant tissues (Nayak and Das, 2021). CDs have been successfully employed to deliver plasmid DNA, siRNA, and dsRNA for the transformation of plant nuclear and organellar genomes (Schwartz *et al.*, 2020). The lipid exchange envelope penetration (LEEP) model explains intracellular transport based on nanoparticle size and surface charge, which facilitates membrane softening and pore formation for cargo internalization (Wong *et al.*, 2016). Owing to their nanoscale size, CDs can move efficiently through plant vascular tissues. Plasmid-coated CDs have been used to transform nuclear and chloroplast genomes in *Triticum aestivum*, as confirmed by GFP-SPO11 fluorescence analysis (Doyle *et al.*, 2019). In addition to gene delivery, CDs are increasingly being explored for biomolecule sensing and plant biofortification applications (Parra-Torrejon *et al.*, 2023).

**Carbon nanotubes (CNTs)**

Carbon nanotubes (CNTs) are carbon-based nanoparticles with dimensions generally below 4 nm × 0.5 µm. Based on the number of graphene layers, they are classified as single-walled carbon nanotubes (SWCNTs) and multi-walled carbon nanotubes (MWCNTs) (Dunbar *et al.*, 2022). SWCNTs consist of a single rolled graphene sheet with a diameter of 0.5–2.0 nm, whereas MWCNTs are composed of multiple concentric graphene layers forming a tube- within-a-tube structure with diameters of up to 220 nm (Lv *et al.*, 2020). Owing to their high surface-to-volume ratio and strong tensile strength, CNTs can efficiently carry plasmid DNA and other nucleic acids across plant cell walls in a noninvasive manner. This property makes them effective nanocarriers for transient and stable gene expression in plants. Additionally, organelle-targeted LEEP-CNTs have enabled the delivery of biomolecules into chloroplasts and mitochondria, supporting transient gene expression in different plant species without the use of a gene gun (Kwak *et al.*, 2019).

**Metallic nanoparticles (MNPs)**

Metallic nanoparticles (MNPs) are nanometer-sized carriers widely used for biomolecule delivery in plants. They are mainly classified into gold nanoparticles (AuNPs) and metal oxide nanoparticles (MONPs) (Law *et al.*, 2023), with sizes generally ranging from 5 to 14 nm (Squire *et al.*, 2023). Among them, AuNPs are extensively used in plant biotechnology because they efficiently bind thiolated nucleic acids, protect them from nuclease degradation, and have a high cargo-loading capacity (Li, 2002). AuNP-mediated delivery is considered an effective alternative to Agrobacterium-mediated transformation (AMT), as it enables the efficient transport of biomolecules across the plant cell wall with minimal tissue damage (Zhi *et al.*, 2022). Delivery efficiency largely depends on the nanoparticle size and surface properties. Gold nanoclusters and spherical AuNPs have successfully delivered siRNA into *Arabidopsis* protoplasts and *Nicotiana benthamiana* leaves, achieving nearly 80% gene silencing efficiency. Although smaller spherical AuNPs are often retained within the cell wall, larger AuNPs and gold nanorods can effectively diffuse through the wall and deliver biomolecules to plant tissues (Squire *et al.*, 2023; Zhang *et al.*, 2023).

### LDH-Based Nanocarriers

Layered double hydroxide (LDH) nanosheets are biodegradable and biocompatible clay-based nanomaterials with positively charged layers that enable efficient RNA delivery (Yong *et al.*, 2021) developed dsRNA-loaded LDH nanosheets, termed *BioClay*, which protected dsRNA from nuclease degradation and maintained its stability on leaf surfaces for up to 20 dafter spraying. BioClay also provided protection against CMV infection in *Nicotiana tabacum through* the RNAi pathway. They further demonstrated that LDH nanosheets (~50 nm) could efficiently internalize dsRNA into *Solanum lycopersicum* pollen within 2–4 h, resulting in an 89% reduction in *β-glucuronidase* mRNA expression through RNAi-mediated gene silencing.

### Mechanism of Nanoparticle Uptake and Movement in Plants

The plant cell wall is the primary barrier to nucleic acid delivery because of its small pore size 5–20 nm (Wang *et al.*, 2019). Generally, nanoparticle DNA or RNA complexes must cross both the cell wall and plasma membrane to release their cargo into the cytoplasm. However, the exact mechanism of nanoparticle uptake by plants is not fully understood (Avellan *et al.*, 2019). Studies suggest that nanoparticles may enter cells through lipid membrane exchange, endocytosis, channel-mediated transport or temporary pore formation (Wong *et al.*, 2016; Kwak *et al.*, 2019). An alternative mechanism has been reported in which gold nanoparticles (AuNPs) remain embedded within the cell wall instead of entering the cell. These nanoparticles protected the siRNA from nuclease degradation and acted as reservoirs that gradually released siRNA into plant cells. Nanoparticle uptake varies depending on the type of nanoparticle and plant species (Zhang *et al*. 2022). The translocation of nanoparticles within plants is also not completely understood, although both xylem and phloem are believed to play a role in their movement (Ma *et al.*, 2018).

### Conclusion

Nanoparticle-mediated gene delivery has emerged as a promising and efficient tool for plant genetic transformation. Compared to conventional methods, nanoparticle-based systems cause less tissue damage and provide improved delivery efficiency across different plant species. Nanocarriers, such as carbon dots, carbon nanotubes, metallic nanoparticles, and LDH nanosheets, have shown great potential for delivering plasmid DNA, dsRNA, siRNA, and CRISPR components into plant cells. These nanoparticles also protect nucleic acids from degradation and support both transient and stable gene expressions. Their ability to cross plant cell walls through noninvasive approaches makes them highly valuable in modern plant biotechnology. However, challenges related to delivery efficiency, biosafety, and environmental impact require further investigation. With continued research and optimization of nanoparticle-mediated delivery systems could play a major role in sustainable agriculture, crop improvement, and future plant genome engineering.

### Application and Future Perspective

Nanoparticle-mediated gene delivery is emerging as a powerful alternative to conventional plant transformation methods because of its higher efficiency and reduced tissue damage. Different delivery approaches, especially spray-based techniques, have shown great potential for large-scale, non-invasive applications in plants. Nanoparticles can efficiently transport dsRNA, siRNA, and other genetic materials across plant cell walls, making them valuable tools for gene regulation and crop improvement. Future studies should focus on improving the delivery of CRISPR constructs and enhancing the transformation efficiency in a wider range of plant species. The combination of multiple delivery methods, such as sonication and vacuum infiltration, may further improve nanoparticle uptake and gene transfer. Although many nanomaterials show good stability and bio-compatibility, concerns related to toxicity and environmental safety still require careful evaluation. Safer functionalizing agents and eco-friendly nanomaterials should be explored for sustainable agricultural use. Overall, continued research and optimization will help establish nanoparticle-mediated delivery as an important technology for future plant biotechnologies and sustainable crop production.

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ISSN : 2583-0910
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Article ID : 06/VI/51/0626

# BEYOND FUNCTIONAL FOODS: THERAPEUTIC POTENTIAL OF PROBIOTICS IN HUMAN HEALTH

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## Abstract

Probiotics have evolved from being recognized primarily as functional food components to emerging therapeutic agents with significant clinical potential in human health. Their beneficial effects are increasingly being explored in the prevention and management of various disorders, including gastrointestinal diseases, *Helicobacter pylori* infections, urogenital infections, metabolic disorders, inflammatory conditions and mental health disorders through modulation of the gut–brain axis. Recent advancements have highlighted the role of probiotics in immune regulation, supportive cancer care and personalized therapeutic interventions. Emerging concepts such as precision probiotics, psychobiotics, postbiotics and targeted delivery systems further expand their clinical applicability. However, the therapeutic efficacy of probiotics remains highly strain-specific, and challenges such as dose standardization, inconsistent clinical evidence and safety concerns in immunocompromised individuals continue to limit broader clinical adoption. The transition from conventional probiotic foods to evidence-based therapeutic applications requires robust clinical validation and standardized protocols. This article highlights the current evidence supporting the therapeutic potential of probiotics, discusses key limitations and explores future innovations that may shape their integration into personalized healthcare and next-generation medical interventions.

**Keywords:** Probiotics, Therapeutic applications, Gut microbiota, Psychobiotics, Precision probiotics, Immune modulation and Functional foods.

## Introduction

Probiotics have evolved from being considered simply functional foods to potential therapeutic agents with significant implications for human health. Their role extends beyond general health maintenance to targeted disease management and advanced health applications. This transition is driven by the need for strain-specific clinical applications, which can address various health conditions more effectively. The therapeutic potential of probiotics is vast, encompassing gastrointestinal disorders, metabolic diseases, mental health and immune modulation. However, challenges such as strain specificity, dose standardization and safety concerns in immunocompromised individuals must be addressed to fully realize their potential.

## Probiotics in Disease Management

- **Gastrointestinal Disorders**: Probiotics have shown efficacy in managing conditions like irritable bowel syndrome (IBS), inflammatory bowel disease (IBD) and diarrhea. They help restore gut microbiota balance, enhance intestinal barrier function and modulate immune responses, which are crucial in these disorders (Verma *et al*., 2025) (Karimi & Hosseinzadeh, 2024). Moreover, the integration of probiotics into therapeutic regimens has been supported by evidence demonstrating their ability to improve gut health and mitigate symptoms of gastrointestinal disorders (Mehra *et al*., 2024). As research progresses, personalized probiotic interventions tailored to individual microbiota profiles will emerge as a key strategy for optimizing treatment outcomes.
- **Helicobacter pylori Management**: Certain probiotic strains can inhibit H. pylori colonization, reducing infection rates and associated gastric issues (Rana & Smriti, 2026). This approach highlights the potential of probiotics as adjunctive therapies in H. pylori treatment, enhancing eradication rates and improving gastrointestinal health outcomes (Kumari *et al*., 2025).
- **Urogenital Infections**: Probiotics can help maintain a healthy urogenital microbiota, reducing the incidence of infections (Verma *et al*., 2025). Furthermore, studies indicate that probiotics may help lower oxidative stress and improve tissue health in individuals suffering from recurrent urogenital infections, highlighting their potential as a promising supportive therapy in managing these conditions (Ballini *et al*., 2018). The integration of probiotics into urogenital health strategies may offer a novel approach to preventing recurrent infections and enhancing overall well-being (Lee, 2023). As research continues, the potential for personalized probiotic therapies tailored to individual needs becomes increasingly promising.
- **Metabolic Disorders**: Probiotics have been linked to improved insulin sensitivity, reduced cholesterol levels and better weight management, making them beneficial in conditions like obesity and diabetes (Verma *et al*., 2025). Furthermore, the modulation of gut microbiota by probiotics can lead to improved metabolic health, potentially reducing the risk of chronic diseases associated with obesity and diabetes (Mallappa *et al*., 2022).

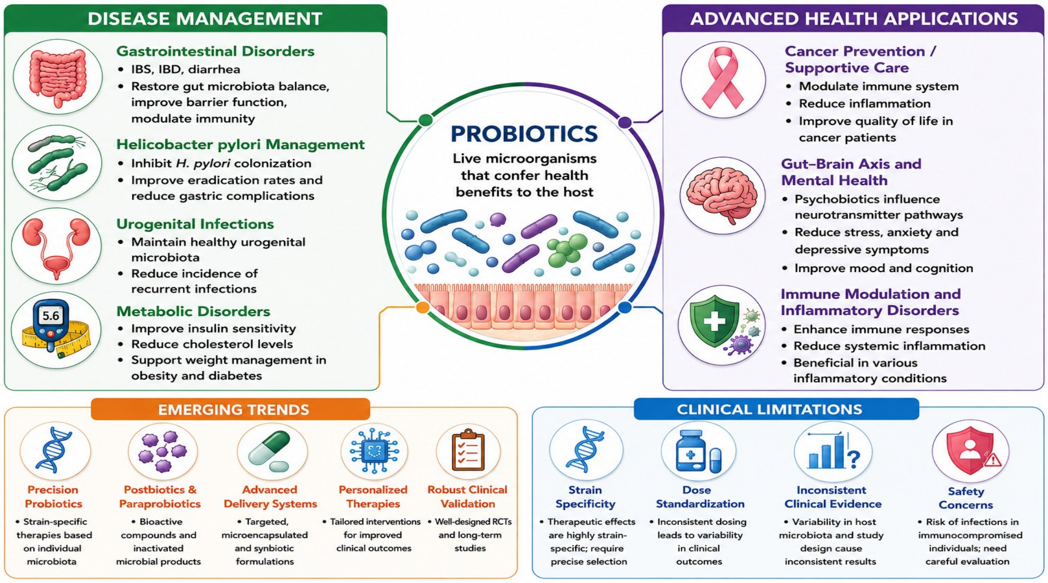

**Fig. 1: Therapeutic Applications of Probiotics in Human Health**

## Probiotics and Advanced Health Applications

- **Cancer Prevention/Supportive Care**: Probiotics play an important role in cancer prevention and as supportive care by modulating the immune system and reducing inflammation. This multifaceted approach highlights the potential of probiotics in enhancing immune responses and improving the quality of life for cancer patients, thereby supporting overall treatment outcomes (Bompalli, 2024).
- **Gut–Brain Axis and Mental Health**: Probiotics, particularly psychobiotics, can influence mental health by modulating neurotransmitter pathways and reducing stress, anxiety and depressive symptoms (Verma *et al*., 2025). Research indicates that psychobiotics enhance mood and cognitive function, suggesting a promising approach for mental health interventions through gut microbiota modulation (Bompalli, 2024).
- **Immune Modulation and Inflammatory Disorders**: Probiotics enhance immune responses and reduce systemic inflammation, which can be beneficial in various inflammatory disorders (Verma *et al*., 2025). This immune modulation not only supports overall health but also play a crucial role in preventing chronic diseases linked to inflammation, such as diabetes and obesity (Dobriyal *et al*., 2024).

## Clinical Limitations

- **Strain Specificity**: The therapeutic effects of probiotics are highly strain-specific, necessitating precise selection for targeted outcomes (Saleem *et al*., 2023). This specificity poses challenges in clinical applications, as not all probiotic strains yield the same health benefits, underscoring the need for tailored probiotic therapies to optimize patient outcomes.
- **Dose Standardization**: Inconsistent dosing regimens contribute to variability in clinical outcomes, highlighting the need for standardized protocols (Sharma *et al*., 2025). Establishing clear dosing guidelines will enhance the reliability of probiotic interventions and facilitate their integration into clinical practice.
- **Inconsistent Clinical Evidence**: Variability in host microbiota and other factors lead to inconsistent results across studies (Rana & Smriti, 2026). To address these challenges, future research should focus on large-scale, high-quality randomized controlled trials that can provide clearer insights into the efficacy and safety of specific probiotic strains in diverse populations.
- **Safety in Immunocompromised Individuals**: Probiotics may pose risks in immunocompromised populations, necessitating careful safety assessments (Saleem *et al*., 2023). To ensure the safe use of probiotics in these vulnerable groups, ongoing research must prioritize establishing robust safety protocols and guidelines tailored to individual health conditions.

## Emerging Therapeutic Innovations

- **Precision Probiotics**: Customizing probiotic strains according to an individual’s specific health needs may improve treatment effectiveness and lead to better therapeutic outcomes (Abouelela & Helmy, 2024). This approach emphasizes the importance of understanding individual microbiota profiles and health conditions to optimize probiotic interventions for various therapeutic applications.
- **Psychobiotics**: These probiotics specifically target mental health by influencing the gut-brain axis (Bompalli, 2024). Recent studies have highlighted the potential of psychobiotics to

improve mental health outcomes by modulating the gut-brain axis, emphasizing their role in addressing disorders such as anxiety and depression (Fathima & Bhat, 2025) (Meyyappan, 2020).

- **Postbiotics**: Utilizing metabolic by-products of probiotics offers health benefits without the need for live microorganisms (Bompalli, 2024). This innovative approach expands the therapeutic landscape, providing alternatives for individuals who may not tolerate live probiotics while still benefiting from their positive effects on health.
- **Targeted Probiotic Delivery Systems**: Advances in delivery systems can improve the efficacy and safety of probiotic therapies (Abouelela & Helmy, 2024). These innovations not only enhance the stability and bioavailability of probiotics but also ensure that they reach their target sites within the gastrointestinal tract effectively.

## Conclusion

Probiotics hold significant promise as therapeutic agents beyond their traditional role in functional foods, offering benefits in disease prevention, immune modulation, metabolic health and mental well-being. However, their successful clinical application depends on strain-specific validation, standardized dosing and robust safety assessment, paving the way for personalized probiotic therapies in future healthcare.

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ISSN : 2583-0910
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monthly newsletter

Article ID : 06/VI/52/0626

# VIRUSES IN A WARMING CLIMATE: EMERGING THREATS TO GLOBAL AGRICULTURE

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## Abstract

Climate change is profoundly altering plant health, with plant viruses emerging as a category of pathogen heavily affected by these shifts. With an increase in temperature, carbon dioxide, drought and storms, and changes in farming systems, the way that viruses survive, spread and cause damage to crops is changing. Viruses require a living organism to survive and are often spread by insect vectors, which means even minor changes in climatic conditions can alter the nature of epidemics quickly . In view of this, viral diseases of plants are now recognized as a threat to crop productivity, quality and food security in many parts of the world. Climate change is not on its own. It is linked to agricultural intensification, global trade, weed reservoir and insect population structure to create conditions for virus emergence and re-emergence. Consequently, diseases formerly confined to certain geographical areas can be spread to new regions, infect new host species and be more challenging to manage. These interlinked processes need to be understood if better strategies for disease management are to be developed in a warming world.

**Keywords**: Climate change, Plant viruses, Emerging viruses, vectors, Epidemiology

## Introduction

Viral diseases in plants are some of the most damaging problems in agriculture because they can cause losses in yield, quality and can compromise the sustainability of agricultural systems over time (Jones, 2021). The viruses are very sensitive to the ecological and climatic changes, unlike many fungal and bacterial pathogens, and often rely on insect vectors for these diseases to spread, which makes them highly susceptible to change (Tsai *et al*., 2022). The environmental conditions can change, and so can the balance between host, virus, and vector in many cases, shifting toward the development of the disease (Garrett *et al*., 2006) .Emerging and re-emerging plant viruses are particularly important as they may spread quickly under favorable conditions and cause epidemics in a region where plants have not previously encountered or been resistant to the virus (Jones, 2009). The outbreaks tend to be localized in intensively farmed regions with high host density, frequent movement of planting materials and vectors (Jones, 2021). In these types of systems, disease intensity and geographic range can be strongly affected by even small climatic changes (Parrella *et al*., 2022).But it's not just about climate, the spread of viruses is influenced by farming practices, trade networks, as well as the ecology of weeds and wild plants interacting with climate(Jones & Barbetti, 2012). Climate change is an environmental issue, but also a significant plant health problem one that impacts farmers, researchers and policy makers (Garrett *et al*., 2006).

## Temperature Change

Nearly all stages of the infection process are influenced by the temperature, making it one of the most important factors to influence plant virus epidemics (Tsai *et al*., 2022). Warm temperatures can boost the amount of virus in tissues, shorten the incubation period between infection and symptom development, accelerate movement in the plant, and accelerate virus replication (Garrett *et al*., 2006). In an applied context, this is likely to result in infected plants being infective earlier and outbreaks of disease occurring faster (Jones, 2021). Warmer temperatures can also reduce plant's resistance. Certain resistance genes are only effective in a specific temperature range when temperatures go outside of this range, the resistance may be reduced or inoperative (Amari *et al*., 2021). This is relevant because the development of resistance genes in crops is frequently a part of crop breeding programs for the control of viral diseases, and climate change may cause viruses to become less manageable over time (Tsai *et al*., 2022). For instance, viruses can gain entry more easily to tobacco and tomato during warmer seasons, and rendering them more susceptible to viral infection (Amari *et al*., 2021). Many viruses are transmitted by insect vectors which are also highly sensitive to temperature. The aphids, whiteflies, thrips and leafhoppers are ectothermic insects and grow and become active depending on the environmental heat directly (Yamamura & Kiritani, 1998). Their life cycles tend to be shorter in warmer seasons, there will be more generations per year, and the season where they can pick up and pass on viruses will be longer (Tsai *et al*., 2022). In temperate climates, a slight rise in temperature increases the likelihood of a number of additional generations of aphids that can result in significant increases in the number of virus carrying aphids (Yamamura & Kiritani, 1998). Another key factor is the lessening of the severity of winters. With higher-than-average winter temperatures, both vectors and viruses can survive in perennial hosts, weeds or crop residues with greater ease and ensuring survival from one season to the next (Jones, 2021). This can result in earlier outbreaks the following growing season and can also aid movement to new northern or higher altitude areas where the climate was previously unsuitable for the virus vector complex to be present (Tsai *et al*., 2022). By this mechanism, warming increases the disease pressure of other viruses in plants and expands the disease's ecological envelope for many plant viruses.

### Elevated $CO_2$

Another significant climate driver of plant virus interactions is high $CO_2$ in the atmosphere (Tsai *et al*., 2022). Indirect but important impacts on virus susceptibility may be caused by changes in plant growth, leaf chemistry, and carbon and nitrogen balances in tissues as a result of rising $CO_2$ (Tsai *et al*., 2022). Plant defense is related to the nutrient and metabolic energy in the tissue, so any alteration in tissue composition can impact on plant resistance to infection (Garrett *et al*., 2006). The most significant side effect of increased $CO_2$ is N dilution. Increased $CO_2$ can result in a relative decrease in N content of the plant biomass, even though the total biomass may increase (Bredow *et al*., 2025). Nitrogen plays a key role in protein synthesis, which includes proteins in antiviral defense pathways. This can lead to weakened defense mechanisms, such as RNA silencing, which can allow viruses to multiply faster and stay in the plant longer in infected plants (Tsai *et al*., 2022). This change is particularly significant since RNA silencing is one of the main antiviral mechanisms in plants. It involves proteins and enzymes that recognize viral RNA and facilitate its degradation to prevent excessive multiplication of the virus (Bredow *et al*., 2025). When the plant's ability to do this is reduced by elevated $CO_2$, the virus has a better opportunity of propagating systemically. In certain crops this can lead to high viral loads without the presence of obvious disease symptoms in the field, thus making infected plants a potential source of virus in the crop (Jones, 2021). High levels of $CO_2$ also affect the feeding behavior of insects. When leaf N is decreased, some vector insects may feed more frequently or for longer periods due to the lower nutritional quality of the plant sap in which they feed (Tsai *et al.*, 2022). This implies that high $CO_2$ could indirectly have an effect on virus transmission by making vectors more active feeders. Weaker plant defenses and changed vector behavior may lead to $CO_2$ enrichment becoming an important determinant of future plant virus epidemics (Bredow *et al.*, 2025).

### Extreme Weather Events

Under climate change, extreme weather events have become more frequent and more severe, and have a strong impact on the epidemiology of plant viruses (Jones, 2021). The physiological or behavioral changes of the host or vector caused by drought, heat, storms and cyclones can be intensified in a way that increases viral transmission. The effects of these events are particularly serious because they are rapid and unpredictable, making outbreak forecasting highly difficult. Drought stress is critical. Plants may also experience physiological changes that affect their infection susceptibility and virus carrying capacity during water stress (Van Munster *et al.*, 2017). Water stress can also impact the plant's immune signaling pathways, such as salicylic acid signaling pathways involved in antiviral defense (Jones, 2021). In these circumstances, certain viruses are able to replicate more effectively, while certain vectors are more efficient in their spread. Certain viruses have been found to be significantly more insect vectored during drought. Transmission of cauliflower mosaic virus and turnip mosaic virus can increase dramatically under water stress conditions, for instance, illustrating the effect of environmental stress on disease transmission. Drought stressed plants also might be more attractive or more suitable to vectors, which also adds to the likelihood of infection (Van Munster *et al.*, 2017).

Storms and cyclones present an entirely different category of epidemiological risk. Viruliferous insects, such as aphids, can easily be transported by strong winds for very long distances and viruses can be introduced into new geographical regions almost instantaneously (Irwin & Thresh, 1988). This long distance spread may help to establish diseases in areas where the susceptible hosts are present but the virus is not yet established. Extreme weather events can turn an area problem into a regional outbreak (Jones, 2021).

### Virus Evolution

Not only is the range of viruses changing with climate change, but the evolution of viruses themselves is changing with climate change (Jones, 2009). With longer transmission seasons and larger numbers of vectors, viruses have more chances to replicate and thus more opportunities to mutate (Stobbe & Roossinck, 2016). This can result in the emergence of new variants over time that have different biological characteristics. Mixed infections are particularly significant in this regard. Multiple infections of the same plant can result in recombining and re-assortment leading to novel combinations of characters in new virus lineages (Jones, 2009). The new variants may have different host ranges, levels of virulence, plant movement and/or transmission potential. Such changes can make disease management much more difficult. Variants which are better adapted to warmer or more unstable conditions can also be favored through climate driven selection (Jones, 2021). Certain viruses could be more heat tolerant, vector specialized or host immune system specialized. This will not only result in the spread of existing viruses being hastened, but also make them more aggressive and adaptable (Stobbe & Roossinck, 2016).

### Globalization and Trade

The global movement of plant viruses has been greatly enhanced by global trade and movement of human populations (Jones, 2014). Seed, seedlings, vegetative cuttings and ornamental plants are often moved across borders and viruses have the ability to be carried without visible symptoms (Jones, 2021). If such infected material is introduced into a new area, the virus can infect rapidly, depending on the climate in the area and the presence of the appropriate vector species. This is made worse by climate change as the climate can become more favorable for newly introduced viruses to survive and spread (Jones, 2021) i.e. the pathogen is introduced by trade and climate decides its fate. This interaction can be particularly risky in areas where the planting material is sourced from outside the region, or where phytosanitary monitoring is not sufficient (Gilbertson *et al*., 2015) .Virus movement associated with trade is well documented in *pepino mosaic virus* (PepMV). First reported in pepino in Peru and then in tomato crops in the Netherlands, the spread of plant viruses has been occurring at a very rapid pace along commercial routes, cross continentally (Jones, 2014). These viruses can then persist and spread locally via vectors, through seeds and via contaminated plant material.

**Agricultural Practices**

Farm practices can either decrease or increase the risk of virus infection and many current systems are not engineered to pose a barrier to virus transmission (Jones *et al*., 2012). Large monocultures offer permanent host availability for viruses, which enable them to multiply efficiently and continue to spread from plant to plant, without interruption (Stobbe & Roossinck, 2016). Minimized crop rotation also reinforces this effect through a reduced diversity that normally would help to disrupt disease cycles. Other practices that might also influence the microclimate for vectors and viruses are irrigation, protected cultivation and multiple cropping (Jones *et al*., 2012). Whiteflies, aphids, and thrips are all important vectors of viruses, and they are often found in high numbers in high humidity, dense plantings and warm enclosed areas. Under these circumstances, disease outbreaks can be particularly extensive and hard to control. The variability of planting dates and seasonal changes (Garrett *et al*., 2006) also increase risk from climate change. The risk of infection goes up when crops are in the field at times when vectors are abundant. Disease pressure is likely to be higher in times of climate variation combined with intensive agriculture (Jones, 2021).

**Weed Reservoirs**

The presence of weeds and wild plants can be overlooked but is a very important part of virus ecology (Jones, 2021). Numerous crop viruses spend their time outside of the crop between seasons and can be carried even if the primary crop is not present. So these weeds can serve as vectors to pick up the virus and transport it to adjacent fields.

The role of weed reservoirs could increase as a result of climate change, as the mild winters that can enhance survival of weeds, may become more common, while wetter climates could drive more weed growth (Van Munster *et al*., 2017). This allows both viruses and vectors to survive all year round. With crop free periods, weeds can take the place of the crop as a “green bridge” and provide an uninterrupted reservoir for disease (Jones, 2021).

This reservoir function is particularly significant in the early season. Viruliferous insects can also quickly disperse from other weed hosts into the commercial crop, infecting plants before they can build resistance or tolerance (Jones, 2021). This early infection can result in the greatest yield losses.

**Conclusion**

Viral plant diseases are becoming more complex, more prevalent and more impactful due to climate change. Climate change, including warmer temperatures and higher CO2, drought, storms and shifts in agriculture, is making conditions more favorable for the spread of viruses, expansion of vectors, and the evolution of virus. Eradicating viruses is difficult, and global trade and weed reservoirs are also contributing to the spread of viruses to new areas and between seasons. Today's challenge is to create more climate and virus resistant systems in agriculture. This will necessitate the use of resistant varieties, climate-smart breeding, better vector control, better weed management, and enhanced quarantine efforts. Monitoring and integrated disease management will play a crucial role in ensuring the productivity and food security of crops under future conditions.

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ISSN : 2583-0910
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Article ID : 06/VI/53/0626

# SCANNING ELECTRON MICROSCOPIC (SEM) STUDIES ON THE DEVELOPMENTAL STAGES OF THE CASTOR WHITEFLY

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## Abstract

Castor (*Ricinus communis* L.) is an important industrial oilseed crop affected by several sucking pests, among which the castor whitefly (*Trialeurodes ricini*) is one of the most destructive. Both nymphs and adults feed on phloem sap, causing chlorosis, reduced photosynthesis, honeydew deposition, sooty mold development, and ultimately yield reduction. Understanding the morphology and developmental stages of this pest is essential for accurate identification and effective management. The present article describes the developmental stages of *T. ricini* using Scanning Electron Microscopy (SEM). SEM provided detailed visualization of the egg, crawler, nymph, puparium, and adult stages, revealing important structural features such as the pedicellate egg, cuticular sculpturing, spiracles, wax-producing pores, vasiform orifice, mouthparts, and wing venation. Each developmental stage exhibited distinct morphological adaptations associated with feeding, attachment, protection, respiration, and dispersal. The study emphasizes the importance of SEM in improving understanding of whitefly biology and supporting stage-based pest management strategies. Knowledge of these microscopic structures contributes to accurate diagnosis, timely intervention, and integrated pest management practices for sustainable castor cultivation.

**Keywords:** Castor, Castor Whitefly, Biology, Scanning Electron Microscope (SEM)

## Introduction

Castor (*R. communis* L.) is an important non-edible oilseed crop cultivated widely in tropical and semi-arid regions. Its seeds contain 45-55% oil rich in ricinoleic acid, which is extensively used in pharmaceuticals, lubricants, cosmetics, polymers, and several industrial products. Healthy foliage is essential for proper seed development and oil accumulation; therefore, pests affecting leaves directly reduce crop productivity. Among the major sucking pests of castor, the castor whitefly (*T. ricini*) is one of the most destructive. Both nymphs and adults feed on plant sap from the underside of leaves, causing chlorosis, leaf drying, reduced photosynthesis, and honeydew secretion that promotes black sooty mold development. Severe infestations significantly reduce plant vigor and seed yield. Although whiteflies appear as tiny powdery insects to the naked eye, they possess highly specialized microscopic structures that support feeding, attachment, protection, and dispersal. Each developmental stage-egg, crawler, nymph, puparium, and adult-shows distinct structural adaptations. These minute features cannot be observed clearly using ordinary microscopy. SEM provides high-resolution visualization of external structures such as cuticular sculpturing, spiracles, wax-producing pores, mouthparts, and wing venation. SEM not only improves understanding of whitefly morphology but also supports accurate identification and stage-specific pest management strategies.

## Meet the Castor Whitefly

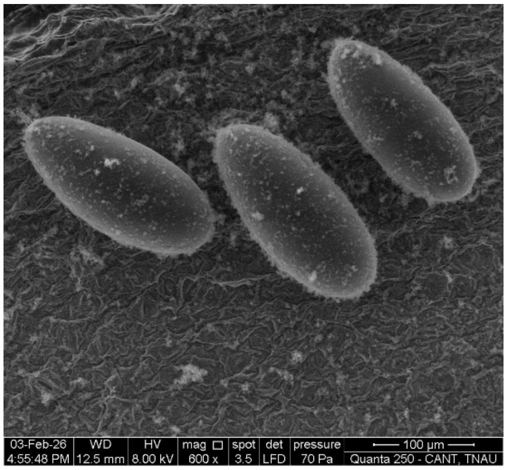
The castor whitefly (*T. ricini*) belongs to the family Aleyrodidae under the order Hemiptera. It is commonly found on castor plants and survives by extracting phloem sap using piercing-sucking mouthparts. Adults are small, soft-bodied insects covered with a white waxy coating and usually remain on the underside of leaves. The immature stages are flattened and scale-like, remaining attached to the leaf surface during feeding. Continuous sap extraction weakens the plant, resulting in yellowing, reduced photosynthesis, premature leaf drying, and drop. Excess sugars consumed during feeding are excreted as honeydew, which encourages the growth of black sooty mold on leaf surfaces. This mold interferes with sunlight penetration and further reduces photosynthetic efficiency. Population buildup is influenced by crop stage and environmental conditions, and multiple generations may develop during the cropping season. Early recognition of symptoms such as yellowing, sticky leaves, and black fungal growth helps farmers detect infestations before severe damage occurs.

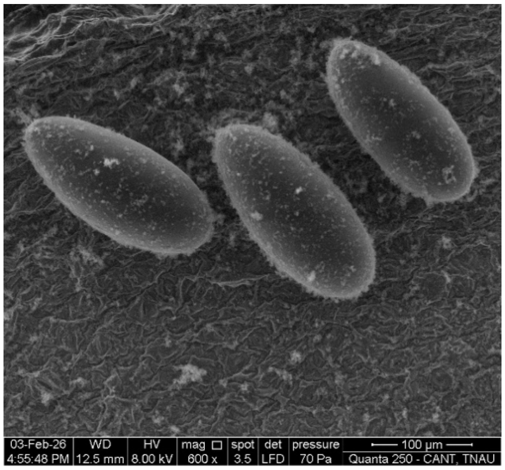
**Why Study Its Life Stages?**

The castor whitefly undergoes several distinct developmental stages: egg, crawler, sessile nymph, puparium, and adult. Each stage differs in structure, behavior, and susceptibility to control measures. The crawler is the only mobile immature stage, while later nymphal stages remain fixed on the leaf surface. The puparium develops a thicker protective covering, and adults become winged for dispersal. Many important diagnostic characters-including spiracles, vasiform orifice, setae arrangement, wax pores, and wing venation-are extremely minute and difficult to observe under conventional microscopes. SEM reveals these structures clearly, helping researchers accurately identify developmental stages and distinguish closely related whitefly species. Understanding these stages is also important for pest management because susceptibility to insecticides and biological control agents varies across developmental stages. Accurate stage identification therefore supports proper timing of management practices.

**The Egg Stage - The Beginning of Infestation**

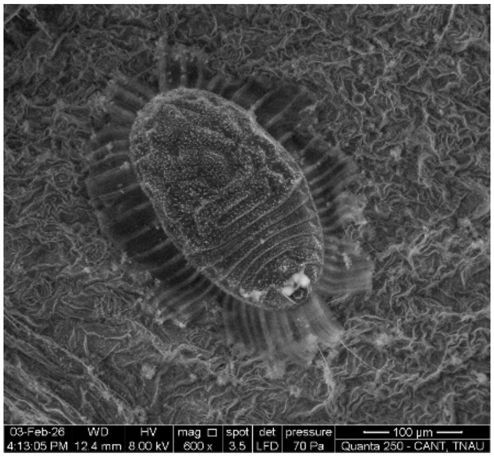
The life cycle begins when female whiteflies deposit eggs on the underside of tender castor leaves. Eggs are often laid in circular or semicircular patterns due to the rotational movement of the female during oviposition. The eggs are microscopic, elongated, and spindle-shaped, measuring about 0.2 mm in length. Under SEM, the eggshell appears smooth and well-defined. Each egg is attached to the leaf surface by a slender stalk called a pedicel, which anchors the egg securely and helps maintain moisture balance. Freshly laid eggs are pale white or greenish but gradually become dark before hatching as the embryo develops inside. Egg clusters serve as the earliest visible sign of infestation and allow early monitoring before feeding damage becomes severe.





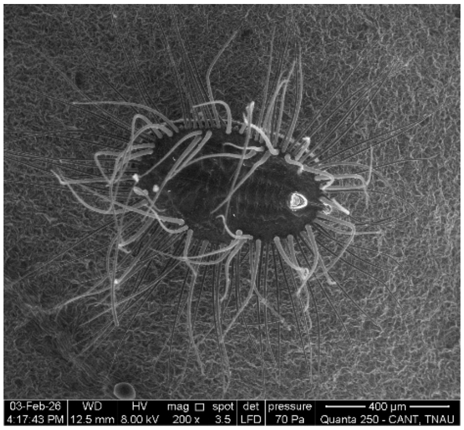
### The Nymph Stage - Active Feeding Phase

After hatching, the insect enters the crawler stage, the only mobile immature phase. The crawler briefly moves across the leaf surface before selecting a feeding site. Once feeding begins, the insect becomes sessile and remains fixed throughout subsequent development. Nymphs are oval, flattened, and closely attached to the leaf surface. Their piercing-sucking stylets penetrate plant tissues and continuously extract phloem sap. Excess sugars are excreted as honeydew. SEM observations reveal detailed dorsal structures, spiracles, marginal outlines, and cuticular patterns that are not visible under normal observation. Heavy infestations during this stage cause severe yellowing, reduced photosynthesis, weakened growth, and premature leaf drying. Because nymphs feed continuously and remain attached for long periods, they contribute significantly to crop damage.



### The Puparium - Transformation Stage

The puparium represents the final immature stage before adult emergence. Although commonly referred to as a pupal stage, it is technically the fourth nymphal instar. During this stage, internal reorganization produces adult structures such as wings, compound eyes, and reproductive organs. The body becomes thicker and more rigid, forming a protective outer covering. SEM clearly reveals the elevated marginal rim, dorsal sculpturing, spiracles, wax pores, and setae. One of the most important diagnostic structures visible under SEM is the vasiform orifice located on the posterior region of the body, a characteristic feature of whiteflies. The insect remains immobile during this stage until the adult emerges through a split in the dorsal surface.



### The Adult Whitefly - The Dispersal Stage

Adult whiteflies are tiny, winged insects measuring approximately 1-1.5 mm in length. Their bodies and wings are covered with fine powdery wax that reduces water loss and protects against environmental stress. SEM studies reveal prominent compound eyes, segmented antennae, delicate wing membranes, and reduced venation patterns characteristic of the family Aleyrodidae. Adults possess piercing-sucking mouthparts like those of the nymphs. Unlike immature stages, adults are capable of flight and disperse rapidly between plants and fields. After mating, females lay eggs on suitable leaves, initiating a new generation.

### Structural Adaptations Revealed by SEM

SEM revealed that every external structure of *T. ricini* is specially adapted for survival on castor plants. The cuticular sculpturing observed on the body surface strengthens the insect and helps maintain structural stability during development. Wax-producing pores present on the body, and wings secrete a protective waxy coating that minimizes moisture loss and shields the insect from environmental stress. The flattened body shape of the nymphal stages allows close attachment to the leaf surface, ensuring stable feeding and protection from displacement. In the egg stage, the pedicel firmly anchors the egg to the plant tissue and helps maintain moisture balance. The piercing-sucking mouthparts are highly specialized for continuous sap extraction from plant tissues, while spiracles and respiratory openings facilitate efficient gas exchange. Together, these structural adaptations enable the castor whitefly to feed, survive, reproduce, and successfully establish populations on castor plants.

### Why This Matters to Farmers

The castor whitefly is not merely a microscopic curiosity; it is a major economic pest affecting castor productivity. Understanding its life stages helps farmers adopt timely and effective management practices. Early detection prevents severe infestations and reduces crop loss. Since susceptibility varies across developmental stages, stage-based management improves control efficiency. Insect growth regulators are often more effective against immature stages, while contact insecticides target adults more successfully. Knowledge of the whitefly life cycle also supports Integrated Pest Management (IPM), which combines monitoring, biological control, cultural practices, and selective pesticide use. Timely interventions reduce unnecessary pesticide applications, preserve beneficial insects, and improve economic returns.

### Conclusion

The castor whitefly completes a highly specialized developmental cycle consisting of egg, crawler, nymph, puparium, and adult stages. Each stage possesses unique structural adaptations that support feeding, protection, respiration, and dispersal. SEM reveals these microscopic details with remarkable clarity, exposing structures that cannot be observed through routine examination. By connecting morphology with biological function, SEM improves understanding of whitefly development and supports accurate identification. Most importantly, knowledge of these developmental stages has direct practical value. Proper identification and stage-based management help reduce crop damage, improve pest control efficiency, and support sustainable castor production. Understanding the microscopic world of *T. ricini* transforms an almost invisible field pest into a clearly understood biological system-an essential step toward effective crop protection.

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ISSN : 2583-0910
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Article ID : 06/VI/54/0626

# BIOPRESERVATION: LACTIC ACID BACTERIA AND ENZYMES TO EXTEND PRODUCE SHELF LIFE

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## Abstract

Global food waste is heavily driven by postharvest decay, which spoils up to 40% of fresh produce before it ever reaches consumers. While synthetic fungicides and chemical washes traditionally combat this issue, rising environmental and health concerns are pushing the industry toward cleaner alternatives. Biopreservation offers a promising, clean-label solution using lactic acid bacteria (LAB) and microbial enzymes. LAB defend produce by forming protective colonies and secreting natural antimicrobials like organic acids. Simultaneously, enzymes like chitinases break down fungal cell walls, while oxidoreductases prevent browning. Applied via edible coatings, this approach faces scalability and regulatory hurdles but remains a vital frontier.

**Keywords:** Biopreservation, Lactic acid bacteria, Microbial enzymes, Postharvest decay, Shelf life extension.

## Introduction

Postharvest fresh produce decays rapidly due to high moisture, active respiration, and opportunistic pathogens like *Botrytis cinerea*. While synthetic fungicides and chemical washes traditionally mitigate these losses, rising microbial resistance and consumer demands for chemical-free, organic food have forced an industry shift. Energetically costly physical methods like cold storage offer incomplete protection. Consequently, biopreservation utilizing Lactic Acid Bacteria (LAB) and microbial enzymes has emerged as a sustainable alternative. Having attained GRAS and QPS safety statuses, LAB actively outcompetes pathogens for space and nutrients while secreting antimicrobials. Simultaneously, targeted enzymes degrade fungal cell walls, effectively securing shelf life without compromising produce quality.

## Lactic Acid Bacteria (LAB) as Biopreservative Shields

Lactic acid bacteria (LAB) including genera like *Lactiplantibacillus, Leuconostoc, Pediococcus, and Weissella,* safeguard fresh produce by colonizing surfaces and forming a protective biochemical barrier. Their primary defense is carbohydrate fermentation, which generates lactic and acetic acids and drops the local pH. When this pH falls below the acids' pKa values (3.86 for lactic, 4.76 for acetic), the acids remain uncharged and undissociated (HA). This allows them to effortlessly penetrate the lipophilic membranes of target pathogens. Once inside the neutral cytoplasm, the acids dissociate into $H^+$ and $A^-$ ions; the resulting proton flood forces the pathogen to exhaust its ATP pumping them out, ultimately collapsing its energy reserves and killing the cell.

**Table 1: Prominent Lactic Acid Bacteria (LAB) strains, their primary antimicrobial secretions, and targeted postharvest pathogens in fresh produce.**

| LAB Strain | Primary Active Metabolites | Target Postharvest Pathogen | Tested Fruit/ Vegetable Matrix |
|---|---|---|---|
| *Lactiplantibacillus plantarum* | Phenyllactic acid, Lactic acid, Plantaricins | *Botrytis cinerea, Rhizopus stolonifer* | Strawberries, Table Grapes |
| *Leuconostoc mesenteroides* | Acetic acid, Mesenterocins, Dextran polymers | *Pectobacterium carotovorum* | Leafy Greens, Cut Carrots |
| *Lactococcus lactis* | Nisin A, Lactic acid, Hydrogen peroxide | *Listeria monocytogenes* | Fresh-cut Melons, Apple Slices |
| *Pediococcus acidilactici* | Pediocin PA-1, Lactic acid | *Pseudomonas fluorescens* | Ready-to-eat Mixed Salads |

Beyond acidification, LAB deploy a sophisticated chemical arsenal to suppress spoilage. They produce ribosomally synthesized peptides called bacteriocins; for instance, Class I lantibiotics like nisin bind to lipid II, halting cell wall synthesis and drilling pores that leak vital ions and ATP. Furthermore, LAB utilize flavoprotein oxidases to generate hydrogen peroxide ($H_2O_2$), which reacts to form destructive hydroxyl radicals (•OH) that shatter pathogen DNA and lipids. Heterofermentative strains also release diacetyl from citrate metabolism, blocking nutrient transport by binding to essential arginine residues. Finally, specialized strains produce antifungal compounds like phenyllactic acid and cyclic dipeptides, which disrupt membrane permeability and enzyme networks to defend produce against destructive molds like *Aspergillus* and *Penicillium*.

### Microbial Enzymes as Postharvest Tools

Purified microbial enzymes offer a highly targeted, non-living alternative to lactic acid bacteria for preserving fresh produce. Soil microbes like Trichoderma and Bacillus produce specialized enzymes that systematically dismantle pathogen defenses. Chitinases chop up the β-1,4-glycosidic bonds in the fungal cell wall using a dual attack: endochitinases slice internal structures randomly, while exochitinases strip pieces from the ends. Simultaneously, β-1,3-glucanases break down the supporting glucan polymers. This combined assault causes the tips of invading fungal hyphae to swell and burst from internal pressure. For bacterial threats, bacterial lysozymes dissolve the peptidoglycan walls of Gram-positive spoilage organisms, successfully halting decay before it spreads.

These biocatalysts also combat enzymatic browning, a common issue in sliced produce like apples and avocados. Browning occurs when cell damage allows polyphenol oxidase (PPO) to turn natural phenols into dark melanin pigments. To disrupt this, glucose oxidase (GOX) converts glucose and oxygen into gluconic acid and hydrogen peroxide. This reaction preserves produce through a two-pronged mechanism: it consumes oxygen trapped in the packaging to starve aerobic molds and PPO, and it generates gluconic acid to drop the surface pH well below PPO's optimal functional range.

### Synergy and Modern Formulation Methods

Combining live Lactic Acid Bacteria (LAB) with cell wall-degrading enzymes creates a powerful, flavor-friendly preservation system. The enzymes weaken fungal walls, allowing LAB’s organic acids to easily penetrate and destroy inner membranes. To scale this commercially, processors embed the mixture into edible biopolymer coatings made from materials like chitosan or sodium alginate.

When sprayed or dipped onto fresh produce, this formulation forms a thin, semi-permeable film. This micro-layer acts as a physical barrier that slows down respiration and locks in moisture to maintain firmness, while the trapped LAB continuously secrete protective compounds to block pathogens during transit.

**Table 2: Ingredient breakdown and function of a typical biopreservative edible coating formulation.**

| Component Class | Specific Ingredient Used | Typical Content | Primary Function |
|---|---|---|---|
| Base Biopolymer | Low-molecular-weight Chitosan | 1.5% - 2.0% (w/v) | Creates the physical film; possesses natural antimicrobial properties |
| Plasticizing Agent | Vegetable Glycerol | 0.5% - 0.8% (w/v) | Keeps the dried coating flexible, preventing cracks or peeling |
| Biopreservative Culture | *Lactiplantibacillus plantarum* | $10^8$ - $10^9$ CFU/mL | Provides continuous, long-term production of organic acids and PLA |
| Targeted Enzyme | Microbial Chitinase | 50 - 100 U/ mL | Actively degrades fungal structures, working synergistically with the LAB |
| Surfactant | Tween 80 | 0.1% - 0.2% (v/v) | Lowers surface tension, helping the mix coat waxy fruit skins evenly |

### Impact on Produce Physiology and Quality Metrics

Biopreservation extends the shelf life of harvested crops by actively regulating their metabolism, rather than just killing surface pathogens. Fresh produce degrades based on its respiration and ethylene release rates. Climacteric fruits, like bananas, experience sharp spikes in both during ripening, causing rapid softening and nutrient loss, while non-climacteric crops, like strawberries, suffer from moisture loss. Applying Lactic Acid Bacteria (LAB)-loaded coatings creates a mild, internal modified atmosphere by restricting oxygen flow. This oxygen scarcity suppresses the enzyme ACC oxidase, delaying the ripening-inducing ethylene spike and preventing protopectin from breaking down, which ultimately preserves structural firmness.

This approach protects the nutritional value of fresh crops against storage-related oxidative stress. The presence of LAB triggers a gentle defense response in plant tissues, boosting the enzyme Phenylalanine Ammonia-Lyase (PAL) to increase antioxidant capacity and natural polyphenol levels. Meanwhile, the low-oxygen environment shields delicate nutrients like Vitamin C from oxidizing, maintaining nutritional quality throughout distribution.

### Commercial Bottlenecks and Industrial Realities

Scaling up lactic acid bacteria (LAB) and enzyme treatments from the lab to industrial packhouses introduces heavy financial and operational hurdles. Standard growth media are too expensive for bulk agriculture, forcing a shift toward cheaper fermentation by-products like molasses or whey. Once produced, keeping delicate cells alive and enzymes intact through erratic supply chains—where they face heat spikes and harsh sanitizers—is a major battle. This rapid degradation forces a reliance on costly stabilization methods like microencapsulation. Operationally, these biological tools risk ruining fruit quality and failing regulatory checks. Warm shipping conditions can cause LAB to consume natural sugars, triggering unintended fermentation that leads to foul odours, sour flavors and mushy textures.

## Conclusion

Biopreservation using lactic acid bacteria and targeted microbial enzymes offers a sustainable alternative to synthetic chemical treatments for fresh produce. By combining natural microbial competition with enzyme activity, this approach safely suppresses decay and preserves structural firmness. However, widespread commercial adoption requires reducing processing costs, improving live cell stability, preventing unwanted fermentation flavours, and securing regulatory approvals. The future lies in using genomics to identify resilient, crop-specific strains and integrating these bio-formulations into biodegradable, active packaging for smart storage. Overcoming these technical and economic hurdles will establish biopreservation as a core pillar of sustainable supply chains, cutting postharvest losses.

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ISSN : 2583-0910
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Article ID : 06/VI/55/0626

# QUEEN, WORKERS AND DRONES- THE POLITICS INSIDE A BEEHIVE

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## Abstract

Honeybee colonies are among nature's most complex social groups, functioning as a "superorganism" where thousands of bees work together seamlessly. This article examines the political structure of a beehive, focusing on the three castes-the queen, workers, and drones-and their roles in keeping the colony stable. We look into how castes are determined, how the queen controls reproduction through chemical signals, the famous waggle dance, and the social systems that ensure the colony’s survival. Understanding these complex relationships offers valuable insights into social evolution and group decision-making in nature.

## Introduction

The honeybee colony (*Apis mellifera*) is a striking example of social organization in the animal kingdom. Within the dark, waxy corridors of a beehive, a sophisticated society exists, captivating scientists, philosophers, and naturalists for centuries. From Aristotle's studies in ancient Greece to modern genetic research, bees have revealed deep insights into cooperation, communication, and shared intelligence.

A typical honeybee colony features one queen, tens of thousands of sterile female workers, and several hundred male drones during the breeding season. Despite its large size, the colony operates as a unified “superorganism,” where individual interests give way to the collective good. Each bee has a specific role, and together they maintain balance, reproduce, gather food, and protect their home with remarkable efficiency.

Unlike human political systems, which rely on elections and laws, beehive politics function through chemical signals, behaviour, and evolutionary processes developed over about 100 million years. The similarities between human and bee societies are noteworthy: both have hierarchies, labour divisions, reproductive rules, advanced communication methods, and ways to make collective decisions.

## The Caste System: Born to Serve

### Three Distinct Castes

Honeybee colonies have three distinct types of individuals, each with specific roles determined by genetics and diet during development.

**Table 1: Characteristics of Honeybee Castes**

| Caste | Sex | Number | Development | Primary Role |
|---|---|---|---|---|
| Queen | Female | 1 | 16 days | Egg-laying |
| Worker | Female | 10,000-60,000 | 21 days | Colony maintenance |
| Drone | Male | 100-1,000 | 24 days | Mating |

**Caste Determination: Nature vs. Nurture**

The differences between the castes are not random; they arise from a fascinating mix of fertilization and diet. Both queens and workers are genetically female (diploid) and develop from fertilized eggs, while drones are male (haploid), developing from unfertilized eggs through a process called arrhenotoky.

The main difference between a queen and a worker is triggered solely by nutrition, leading to significant epigenetic changes. A female larva destined to become a queen is fed only royal jelly-a protein-rich secretion from nurse bees-throughout her larval development. In contrast, worker-bound larvae receive royal jelly only for the first three days, then switch to a diet of pollen and honey (bee bread). This dietary change alters the DNA methylation patterns in the developing bee, essentially silencing worker traits and activating the pathways needed for a queen's anatomy and functional ovaries.

**Reproductive Control: The Queen's Dominion**

**Queen Mandibular Pheromone (QMP)**

The queen keeps her reproductive control mainly through chemical communication. The Queen Mandibular Pheromone (QMP), produced in her mandibular glands, is a key social regulator in the colony. QMP acts as both a releaser pheromone, triggering immediate responses, and a primer pheromone, causing long-lasting physiological changes. When workers detect QMP, they create a "retinue" around the queen, grooming her and spreading the pheromone throughout the colony.

**Worker Policing: The Collective Enforcer**

Despite the queen's chemical influence, some workers may develop functional ovaries and try to lay eggs. The colony deals with this through "worker policing," a behaviour where workers find and remove eggs laid by other workers. Research by Ratnieks and Visscher (1989) showed that worker-laid eggs are eliminated within hours, while queen-laid eggs are accepted and cared for. Since the queen mates with many different males, most workers are only half-sisters. Evolutionarily, it makes more sense for them to raise the queen's offspring than to let their half-sisters' lay eggs.

**Communication: The Language of Bees**

**The Waggle Dance: A Nobel Discovery**

One of the most famous aspects of bee communication is the waggle dance, discovered by Austrian zoologist Karl von Frisch in the 1940s. For this groundbreaking research, von Frisch received the Nobel Prize in Physiology or Medicine in 1973, which he shared with Konrad Lorenz and Nikolaas Tinbergen for their discoveries regarding individual and social behaviour patterns.

When a forager finds a rich food source, she returns to the hive and performs a figure-eight dance on the vertical comb. The dance conveys precise information.

**Pheromonal Communication**

In addition to the waggle dance, bees communicate a great deal through pheromones. The alarm pheromone, released when a bee stings, notifies other bees of danger, and can trigger coordinated defensive actions. The Nasonov pheromone helps guide foragers back to the hive entrance. Brood pheromone affects worker behaviour and developmental rates.

**Table 2: Major Pheromones in Honeybee Communication**

| Pheromone | Source | Function |
|---|---|---|
| Queen Mandibular | Queen's mandibular glands | Suppresses worker reproduction, attracts retinue |
| Alarm pheromone | Sting gland | Alerts nestmates to danger |

| Pheromone | Source | Function |
|---|---|---|
| Nasonov | Nasonov gland (abdomen) | Orients foragers to hive entrance |
| Brood pheromone | Larval salivary glands | Stimulates foraging and nursing |

## Social Regulation: Division of Labor

### Temporal Polyethism

Worker bees progress through a series of age-related tasks known as temporal polyethism.

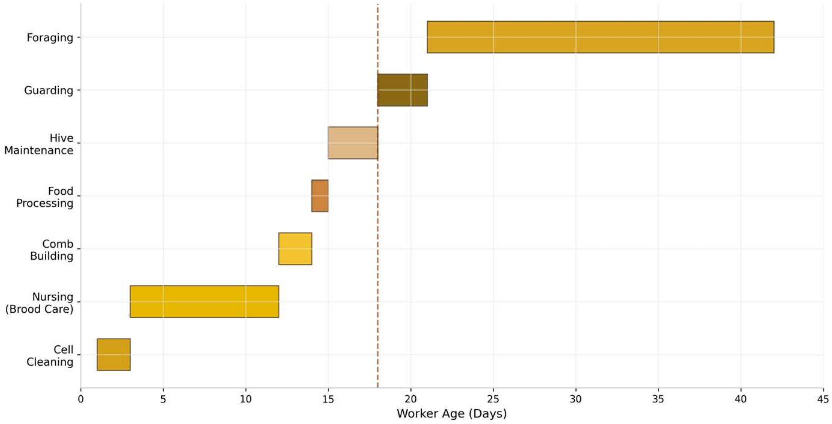

***Figure 1: Age-based division of labour (temporal polyethism) in worker bees***

Under normal conditions, young workers start with safe, indoor jobs like cleaning cells and caring for the brood. As they get older, they move on to more demanding tasks, culminating in foraging—the most dangerous job, which exposes them to predators, weather, and fatigue. However, this division of labour is not a strict timeline; it is a flexible system regulated by Juvenile Hormone (JH) levels and the immediate needs of the colony. This adaptability ensures that all essential colony tasks are completed efficiently, regardless of external challenges. For example, if a hive loses a significant number of foragers to predators or pesticides, younger house bees will experience a swift rise in JH, maturing more quickly to take on outdoor jobs and stabilize the colony.

### Colony Homeostasis

The colony acts as a superorganism, maintaining internal balance much like a single organism. Workers manage the hive temperature at about 35°C (95°F) by fanning to cool or clustering and shivering to warm. They control humidity for proper honey curing and protect against intruders and diseases.

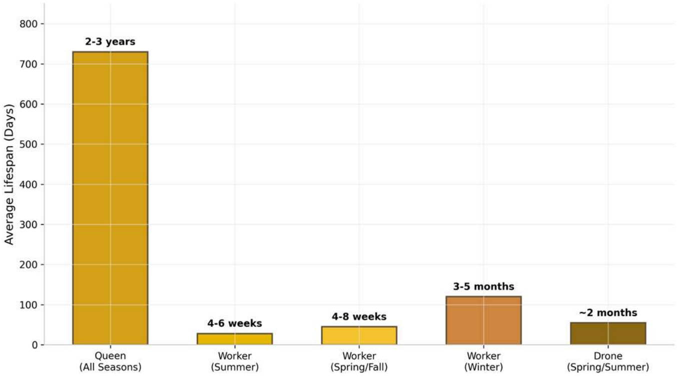

***Figure 2: Lifespan variation among honeybee castes and seasonal worker differences***

**Swarming: Colony Reproduction**

When a colony gets too crowded, it reproduces through swarming. In this process, the old queen leaves with about half the workers to start a new colony. Before leaving, the workers build special queen cells and raise new queens. The first emerging queen usually eliminates her rivals, ensuring she takes over the original colony.

Swarm decision-making shows impressive collective intelligence. Scout bees assess potential nesting sites and "vote" for their preferred location by varying the intensity of their dance. Research has indicated that this democratic approach often selects the best site available (Seeley, 2010).

**Conclusion**

The politics within a beehive reveal a complex social system that has developed over millions of years. Through chemical signals, behavioural patterns, and group decision-making, honeybee colonies achieve impressive coordination without centralized control. The queen's pheromonal influence, worker policing, the waggle dance, and age-based task division all play a part in the colony's success.

Understanding these mechanisms not only feeds our curiosity about the natural world but also inspires human design systems. From distributed computing methods modelled on bee behaviour to insights into social organization, the beehive continues to provide valuable lessons about cooperation, communication, and collective intelligence.

As we confront global challenges like pollinator decline, understanding the complex politics of beehives becomes increasingly crucial for conservation efforts. It is vital for the survival of these remarkable insects, which play such an important role in our ecosystems and agriculture.

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ISSN : 2583-0910
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Article ID : 06/VI/56/0626

# HORIZONTAL GENE TRANSFER: ACCELERATING MICROBIAL EVOLUTION

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## Abstract

Microorganisms are the smallest living organisms present in vast numbers across diverse environments. They play a dual role in human life, acting as both beneficial allies and harmful pathogens. Beneficial microbes contribute to nutrient cycling, food production, biotechnology, and medicine, while pathogenic ones cause diseases that threaten health and food security. Their remarkable adaptability, driven by rapid growth rates and genetic flexibility, enables them to thrive in extreme environments and evolve resistance to stress factors such as antibiotics. This article explores the application of horizontal gene transfer in microbial evolution, antibiotic resistance and its application in various fields of science and technology.

**Key Words:** Horizontal gene transfer, Microbial evolution, Antibiotic resistance, Conjugation, Transformation, Transduction

## Introduction

Microorganisms are the smallest living creatures that we can't see with our naked eyes. They are present everywhere in large numbers and are both beneficial and harmful to human beings. These microbes are among the most adaptable life forms on the planet due to their increased growth rate and genetic flexibility. Microorganisms are not only abundant but also indispensable to life on Earth. They drive critical ecological processes such as nutrient cycling, decomposition, and nitrogen fixation, ensuring that ecosystems remain balanced and productive. In human society, they are harnessed for the production of antibiotics, vaccines, fermented foods, and biofuels, making them silent partners in our daily lives. At the same time, pathogenic microbes remind us of their potential harm, causing diseases that challenge public health and food security.

What makes microorganisms truly remarkable is their adaptability. With rapid growth rates and genetic flexibility, they can survive in extreme environments; from boiling hot springs to frozen glaciers and evolve quickly through mutation and horizontal gene transfer. This resilience allows them to resist antibiotics, colonize diverse niches, and thrive under conditions that would be hostile to most other life forms. Their ability to adapt so swiftly is both a scientific marvel and a pressing concern for medicine and agriculture.

## Horizontal Gene Transfer

Horizontal gene transfer (HGT) is the movement of genetic material between organisms without reproduction. Unlike vertical gene transfer, where genes pass from parent to offspring, HGT allows microorganisms to rapidly acquire new traits from unrelated organisms. This process plays a major role in microbial evolution by increasing genetic diversity and helping microbes adapt quickly to changing environments. The three main mechanisms of HGT are transformation (uptake of free DNA), transduction (gene transfer through bacteriophages), and conjugation (direct transfer of DNA between cells).

## Mechanisms of Horizontal Gene Transfer

Transformation, transduction and conjugation are three primary mechanisms of horizontal gene transfer (HGTs) in bacteria. In the **transformation** process, when the nearby bacterial cell dies and its cell wall is lysed, it's genetic material is released into the environment in fragments. A living bacterial cell can pull these fragments by its own membrane and at the last incorporate them into its chromosome.

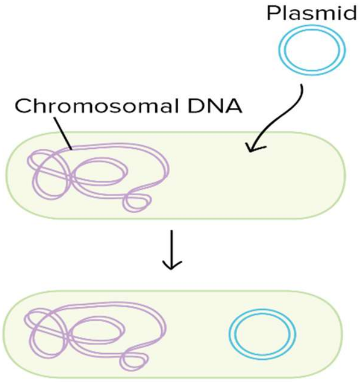

Fig. 1: Transformation process in Bacteria

**Transduction** is the process in which genetic material is transferred through the bacteriophage, having contact with the bacterial cell, which could be an infected or recipient or our targeted bacterial cell. After the transfer of genetic material into the bacterial cell, it can multiply with the genetic material of the bacterial cell.

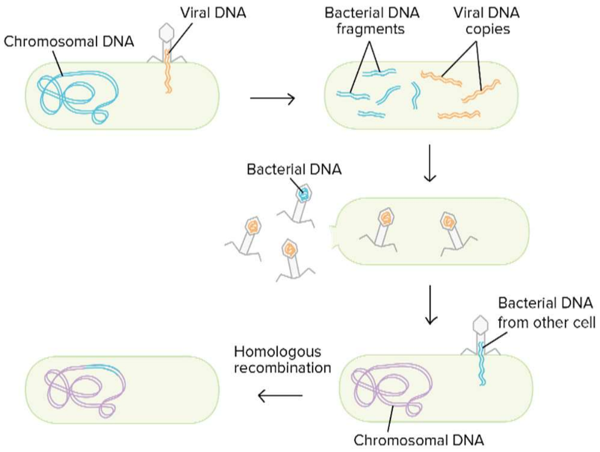

Fig. 2: Transduction process in Bacteria

**Conjuigation** is the process by which genetic material is transferred from one bacterial cell to another through conjugation tube formation. Through this process, we can develop a new drug from the antibody.

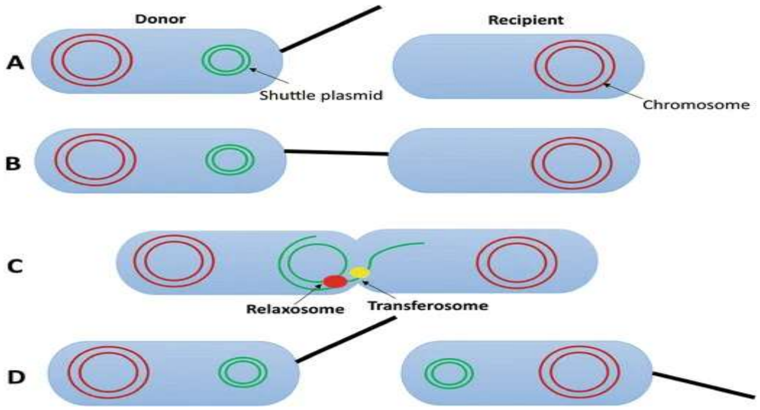

Fig. 3: Process of Conjugation in a Bacteria

Mobile genetic elements have a unique ability to move around within a single cell's genome or also transfer entirely between different bacterial genomes, which act as a segment of selfish DNA. Plasmids are small, circular pieces of extra chromosomal DNA found inside bacteria. Which can be used to transfer the desired DNA piece into the recipient, possibly through the modified into there. Whereas Transposons act like a passenger that is loaded onto the plasmid and also can jump off the plasmid and insert into new bacterial DNA through a cut-and-paste or copy-and-paste mechanism.

### HGT in Antibiotic Resistance

One of the most significant impacts of HGT is the spread of antibiotic resistance. Bacteria can exchange resistance genes through plasmids and other mobile genetic elements, enabling even non-resistant strains to survive antibiotic treatments. The rapid dissemination of multidrug-resistant pathogens has become a major global health concern.

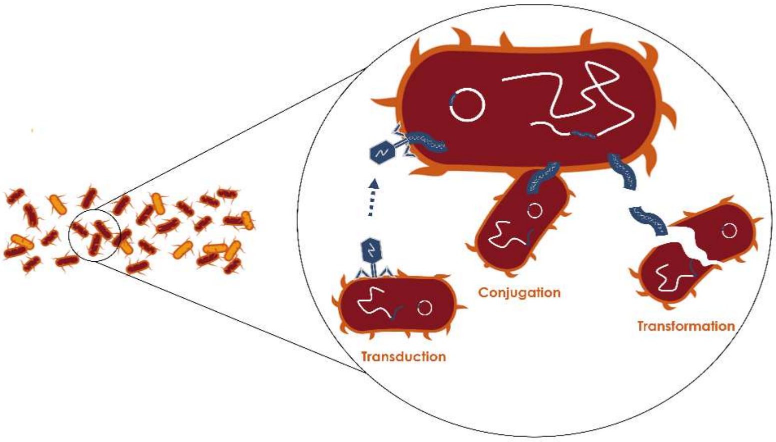

Fig 4: Transfer pf antibiotic resistant gene

### Effect of HGT in Microbial Evolution

By enabling the rapid spread of traits like antibiotic resistance, metabolic pathways, and stress tolerance, HGT accelerates microbial adaptation far beyond what mutations alone could achieve.

As a result, microbial genomes often become mosaics of diverse origins, blurring traditional evolutionary lineages and reshaping ecosystems.

**Application of HGT**

Despite these concerns, HGT also has valuable applications in biotechnology, agriculture, and environmental microbiology. In biotechnology, scientists use HGT-based methods to introduce useful genes into microorganisms for the production of insulin, enzymes, vaccines, and biofuels. In agriculture, beneficial genes can be transferred to crops or plant-associated microbes to improve disease resistance, nutrient uptake, and stress tolerance. Environmental microbiology also benefits from HGT, as microbes with transferred genes can help degrade pollutants, remove toxic compounds, and support bioremediation efforts in contaminated environments.

**Challenges and Future Opportunities of HGT**

However, HGT presents several challenges and risks. The unintended spread of engineered genes into natural ecosystems may disrupt microbial balance and ecological stability. There is also concern about the transfer of antibiotic resistance genes from genetically modified organisms to pathogenic bacteria. Ethical and biosafety considerations, therefore, remain important in research and practical applications involving gene transfer technologies.

Therefore, horizontal gene transfer is a powerful evolutionary mechanism that shapes microbial diversity and adaptation. While it contributes to major challenges such as antibiotic resistance, it also provides important opportunities in medicine, agriculture, and environmental management. Careful monitoring and responsible use of HGT-related technologies are essential to maximize benefits while minimizing risks.

**Conclusion**

Horizontal gene transfer (HGT) is a central driver of microbial evolution, enabling microorganisms to acquire genetic material from unrelated species and thereby expand their genetic repertoire far beyond what vertical inheritance allows. Through mechanisms such as transformation, transduction, and conjugation, microbes can rapidly gain traits like antibiotic resistance, novel metabolic pathways, and stress tolerance, which enhance their survival in diverse and often hostile environments. This genetic exchange blurs traditional evolutionary lineages, creating mosaic genomes that reflect the dynamic and interconnected nature of microbial communities. As a result, HGT not only accelerates microbial adaptation but also poses significant challenges for human health, while simultaneously offering opportunities for innovation in biotechnology, agriculture, and environmental sustainability.

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Article ID : 06/VI/57/0626

# NEXT-GENERATION REMOTE SENSING TECHNOLOGIES: INNOVATIONS AND PRACTICAL APPLICATIONS

**Isha Kumari, Padmanabha A*, Suraj Verma, Harsh Pandey, Ritika A. Tandel, Vivek R. Tandel, Milan B. Ram and Aditya Kumar Upadhyay**

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Remote sensing has become a fundamental technology for observing, analysing, and managing Earth's natural and human systems. It enables the acquisition of spatial and temporal data without physical contact, using advanced sensors mounted on satellites, aircraft, and unmanned aerial vehicles (UAVs). Recent progress in sensor design, data processing, and computational techniques has significantly improved the accuracy, resolution, and efficiency of remote sensing systems. One of the most notable advancements is the integration of Artificial Intelligence and deep learning models, which has led to the emergence of Geospatial Artificial Intelligence (Geo AI). These techniques allow automated extraction of patterns, object detection, and predictive modelling from large-scale geospatial datasets, improving decision-making in real time. Additionally, innovations in hyperspectral imaging now enable the capture of hundreds of spectral bands, allowing precise identification of materials, vegetation stress, and mineral composition. Meanwhile, LiDAR (Light Detection and Ranging) technology has evolved to provide highly accurate 3D spatial data, with millimetre level precision and improved capabilities through integration with AI and multi-sensor systems (He *et al*., 2015). Another major advancement is multi-source data fusion, where data from optical, radar, LiDAR, and hyperspectral sensors are combined to generate comprehensive and high-quality information about the Earth's surface. This approach significantly enhances land monitoring, environmental analysis, and urban modelling. furthermore, the use of drone-based remote sensing has expanded rapidly, offering high-resolution, flexible, and cost-effective data acquisition for localized studies such as precision agriculture and disaster assessment. Emerging trends also include edge computing, real-time satellite data processing, and self-supervised and generative AI models, which reduce dependency on label datasets and improve scalability in remote sensing applications. These technological advancements have broadened the applications of remote sensing across multiple domains, including agriculture, environmental monitoring, disaster management, urban planning, and climate change analysis. By providing accurate, timely, and actionable information, remote sensing plays a crucial role in sustainable development, resource management, and global decision making processes.

**Keywords:** Remote Sensing, Artificial Intelligence, Hyperspectral Imaging, Geospatial Data UAV (Drones), Satellite Imaging

## Introduction

Remote sensing is a key component of Geospatial Science that allows the collection of data about the Earth's surface without physical contact. Using satellites, aircraft, and drones, it provides valuable insights into environmental and human activities. With technological progress, remote sensing has become an indispensable tool for researchers, governments, and industries. Building on a unified theoretical framework grounded in electromagnetic principles and the interactions between electromagnetic fields and Earth's subsurface materials, a novel concept of penetrating remote sensing is proposed through the integration of hyperspectral, electromagnetic, and various multi-physics techniques. By combining the interactions of multiple physical fields, this approach enables comprehensive exploration of the Earth from the surface to deeper interior regions, revealing valuable information about its internal composition. The resulting framework provides detailed images and three-dimensional models that enhance understanding of the distribution, structure, properties, and dynamic behaviour of subsurface material (Wang *et al.*, 2023).

## Concept of penetrating remote sensing

The full-spectrum electromagnetic field encompasses the complete range of electromagnetic radiation, including ultraviolet, visible, infrared, microwave, and other low-frequency electromagnetic waves. Penetrating remote sensing techniques also incorporate static magnetic and gravitational fields as classical potential fields. Developing a unified numerical framework to explain the interactions between electromagnetic fields and multi-physics media is a central objective of penetrating remote sensing, as it enables the effective utilization and control of these waves for deep earth sensing applications. Penetrating remote sensing investigates the interaction between the physical properties of the Earth's surface and subsurface and electromagnetic waves of different frequencies. It is a multidisciplinary research field that includes hyperspectral imaging, electromagnetic techniques, and potential field methods. These methods complement each other in terms of detection depth, resolution, and the type of physical properties they can identify.

The penetration depth of electromagnetic waves is inversely related to their frequency, meaning lower-frequency waves can penetrate deeper into the Earth (Liu *et al.*,2020). Different remote sensing technologies are therefore used to investigate varying depth ranges based on their electromagnetic frequencies (Vickers, 2002). Hyperspectral sensors mainly detect surface reflectance, focusing on interactions between incoming radiation and the Earth's top surface layer. Electromagnetic (EM) detection is a geophysical technique that uses EM fields from airborne or ground-based platforms to study the electrical conductivity of subsurface materials (Rutsch. *et al.*, 2005). Magnetometry measures secondary anomalous static magnetic fields produced under the influence of the Earth's geomagnetic field, which originates from the movement of molten iron in the outer core. Using observed magnetic data, the magnetic susceptibility of near-surface targets and deeper internal structures can be estimated. Gravity field studies, based on the principles of general relativity, enable high-resolution imaging of subsurface density variations, helping identify rock types, faults, mineral deposits, and groundwater reservoirs.

Currently, the quantitative interpretation of multiple physical fields remains challenging because it involves the integration of several scientific disciplines. Combining and correlating different datasets into a unified subsurface model improves interpretation reliability, reduces uncertainty, and enables cross-validation of results obtained from multiple methods and datasets.

## Methodology and technologies of penetrating remote sensing

Scientometrics is an effective method for carrying out data-driven literature reviews, enabling researchers to systematically and quantitatively analyze large volumes of scientific publications (Manivasagam *et al.*, 2024). Scientometric approach was applied to identify key research trends and major thematic areas in the field of Remote Sensing for Irrigation (RSI). The scientometric analysis offers a detailed understanding of the historical progress in the field and helps uncover hidden research trends and patterns. Bibliographic data related to remote sensing and irrigation research from 2003 to 2022 were retrieved from the Scopus database (Pranckutė., 2021). Scopus is widely used in scientometric studies because it provides updated information on scientific publications, enabling the evaluation of research productivity and impact across publications, institutions, and researchers (Baas *et al*., 2020). The development of advanced remote sensing platforms has ushered penetrating remote sensing into a new phase of multi-level, three-dimensional, multi-angle, comprehensive, and all-weather earth observation (Wang *et al*., 2023). Based on their height above the Earth's surface, these platforms are classified into satellite-based, airborne, and ground-based systems. The implementation framework of penetrating remote sensing includes the following major components:

**Multi-physics field coupling simulation**
Electromagnetic waves across different spectral bands are fundamentally governed by the same physical principles. Therefore, simulations of multiple geophysical fields can be integrated within a unified theoretical and numerical framework.

**Multi-physics field feature library**
The multi-physics field observation feature library contains a broad collection of observed characteristics and phenomena across the full electromagnetic spectrum for identifying surface and subsurface targets. This library functions as a reference database that enables comparison between observed geophysical features and known patterns or anomalies.

**Multi-physics coupling inversion**
Based on multi-physics field coupling simulations, a multi-physics inversion framework can be established. This framework enables the simultaneous inversion of different geophysical datasets to generate three-dimensional subsurface models that remain consistent with observations obtained from multiple geophysical methods.

Another important application of penetrating remote sensing is oceanographic profile exploration. By using oceanographic profiling sensors, the capabilities of traditional marine remote sensing can be expanded from two-dimensional observations to three-dimensional analysis. This approach supports applications in biogeochemistry, ecology, ocean dynamics, and target detection. However, three major complex challenges must be addressed during this process.

**Table 1: Comparison Table of Remote Sensing Technologies**

| Technology | Key Feature | Advantages | Applications |
|---|---|---|---|
| Satellite Imaging | Large-scale coverage | Wide area monitoring | Weather, agriculture, mapping |
| Hyperspectral Imaging | Multiple z spectral bands | High accuracy in material detection | Mineral exploration, vegetation |
| LiDAR | 3D surface mapping | High precision elevation data | Forestry, urban planning |
| Drones (UAVs) | Low-altitude sensing | Cost-effective and flexible | Agriculture, disaster management |
| AI Integration | Automated data analysis | Fast and accurate predictions | All sectors |

**Next-generation sensors**
In recent years, the satellite imaging sector has undergone a major transformation toward smaller, cost-effective, and highly flexible platforms, especially Small Sats. These compact satellites support quicker deployment and lower launch expenses, making large-scale Earth observation systems

more accessible for governmental as well as commercial use. Instrumentation capabilities are continuously advancing toward larger scales and higher throughput to study increasingly complex phenomena. In the early stages, commercially available technologies were mainly adapted for phenotyping purposes (Roitsch *et al.*, 2015). More recently, more advanced and specialized acquisition systems have been developed as shown in Fig 1. Today, the growing importance of the high-throughput phenotyping (HTP) field, along with significant technological investments by research groups, is encouraging sensor manufacturers to customize their products for specific plant trait measurements. For instance, industrial Light Detection and Ranging (LiDAR) systems operating in the red wavelength band are now being applied to analyze the spatial distribution of green plant tissues within crop canopies (He *et al.*, 2015).

LiDAR can generate highly detailed 3D models of plant canopies, but it does not provide information on canopy bulk density, which is important for accurate biomass estimation. Biomass estimation can be improved by integrating multiple approaches, such as combining LiDAR-based 3D reconstruction with aerial images and spectral or microwave sensing, using RGB imaging with void-filling techniques, or enhancing contrast between dark and light regions.

The integration of LiDAR and multispectral imaging into a single sensor has been proposed to simultaneously capture structural and biochemical plant traits while overcoming the limitations of passive remote sensing. Such combined systems are already being used in aerial vegetation mapping and land-cover classification, although similar technologies for mobile ground-based imaging remain limited. Developing these systems would greatly improve the speed, precision, and accuracy of field phenotyping, making it possible to estimate the vertical distribution of photosynthetic pigments or nitrogen within plant canopies. Recently, Phenospex introduced a gantry-type multispectral LiDAR system for phenotyping applications, the Plant Eye F500. Equipped with four simultaneous spectral channels in the 400–900 nm range along with 3D point cloud generation, this technology opens new opportunities for advanced trait discovery.

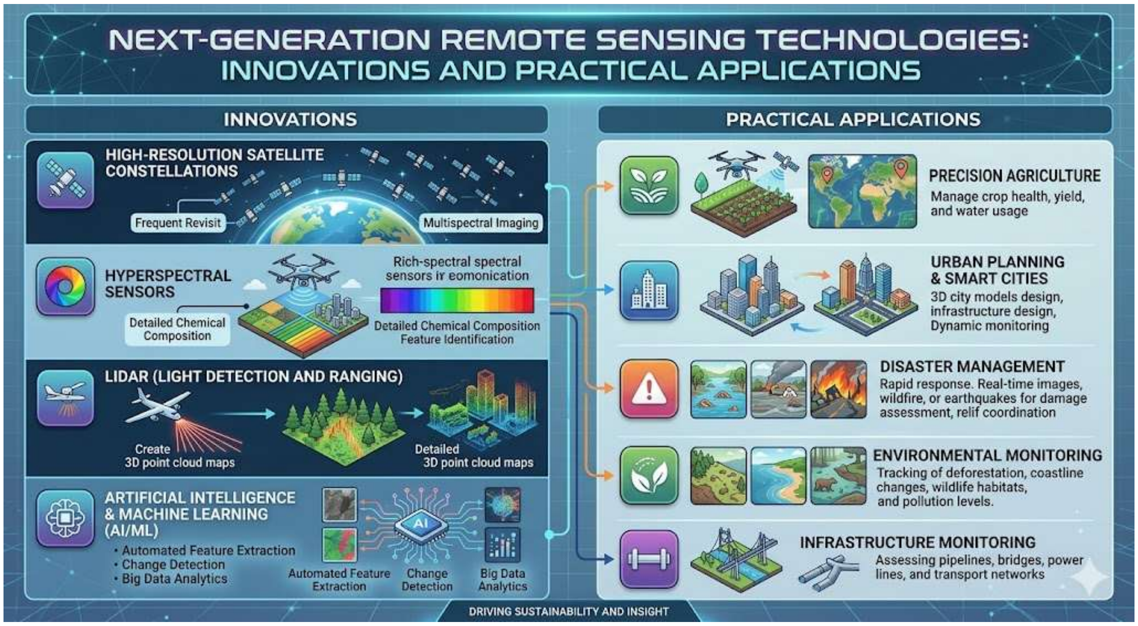


**Fig 1-: Next-Generation Remote Sensing Technologies: Innovations and Practical Applications**

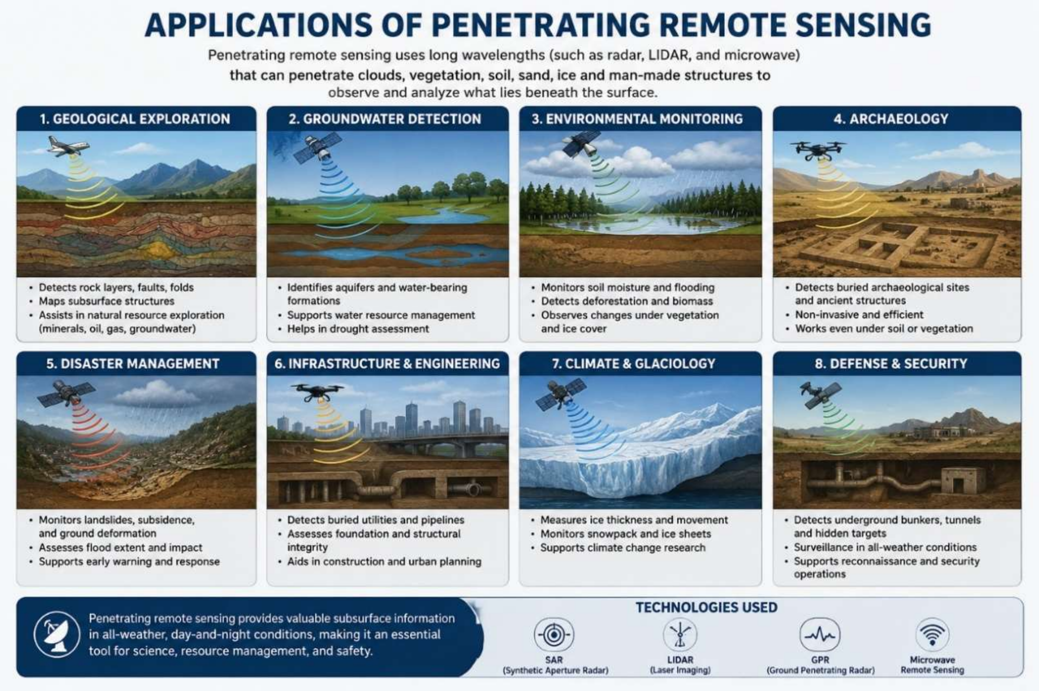
## Applications of penetrating remote sensing

### Transparent geology

The Earth, with a radius of about 6,379 km, is made up of rocks, magma, and molten iron fluids. Despite advancements in geophysical technologies, many scientific mysteries about the Earth's interior still remain unresolved. Satellite based magnetometry and gravimetry are among the few geophysical techniques capable of penetrating several thousand kilometers below the surface to investigate internal Earth structures. Currently, the interpretation of gravity and magnetic data mainly relies on single physical property models, which often provide resolutions lower than practical requirements. By combining multiple datasets and integrating various physical properties, it becomes possible to improve the identification of deep subsurface structures, better map tectonic features, and enhance predictions of mantle and core dynamics (Wang., 2023).

### Transparent urban underground space

Urban environments often contain highly complex subsurface structures, such as multiple underground layers, cavities, buried foundations, and human-induced disturbances. Identifying different underground targets and accurately interpreting geophysical data remain difficult tasks that heavily rely on expert knowledge and supplementary information. In addition, large-scale geophysical techniques often face limitations in terms of coverage and resolution when applied to urban investigations. A promising approach for improving urban subsurface detection is the integration of multiple datasets, including gravity, ground penetrating radar, and electromagnetic methods, through multi-physics coupling inversion technologies that help resolve inconsistencies among different observations.



APPLICATIONS OF PENETRATING REMOTE SENSING

Penetrating remote sensing uses long wavelengths (such as radar, LIDAR, and microwave) that can penetrate clouds, vegetation, soil, sand, ice and man-made structures to observe and analyze what lies beneath the surface.

**1. GEOLOGICAL EXPLORATION**
- Detects rock layers, faults, folds
- Maps subsurface structures
- Assists in natural resource exploration (minerals, oil, gas, groundwater)

**2. GROUNDWATER DETECTION**
- Identifies aquifers and water-bearing formations
- Supports water resource management
- Helps in drought assessment

**3. ENVIRONMENTAL MONITORING**
- Monitors soil moisture and flooding
- Detects deforestation and biomass
- Observes changes under vegetation and ice cover

**4. ARCHAEOLOGY**
- Detects buried archaeological sites and ancient structures
- Non-invasive and efficient
- Works even under soil or vegetation

**5. DISASTER MANAGEMENT**
- Monitors landslides, subsidence, and ground deformation
- Assesses flood extent and impact
- Supports early warning and response

**6. INFRASTRUCTURE & ENGINEERING**
- Detects buried utilities and pipelines
- Assesses foundation and structural integrity
- Aids in construction and urban planning

**7. CLIMATE & GLACIOLOGY**
- Measures ice thickness and movement
- Monitors snowpack and ice sheets
- Supports climate change research

**8. DEFENSE & SECURITY**
- Detects underground bunkers, tunnels and hidden targets
- Surveillance in all-weather conditions
- Supports reconnaissance and security operations

Penetrating remote sensing provides valuable subsurface information in all-weather, day-and-night conditions, making it an essential tool for science, resource management, and safety.

TECHNOLOGIES USED
- SAR (Synthetic Aperture Radar)
- LIDAR (Laser Imaging)
- GPR (Ground Penetrating Radar)
- Microwave Remote Sensing

**Fig 2-: Applications of penetrating remote sensing**

### Conclusion

Recent advances in remote sensing technologies have transformed how we observe and interact with our planet. With the integration of AI and modern sensing tools, the field continues to evolve rapidly. Remote sensing has emerged as one of the most effective methods for observing the distribution patterns of key species while reducing both time and cost. Advances in analytical techniques, growing computational power, improved sensor fusion and networking capabilities, along with free access to satellite data, have further enhanced its applications and efficiency (Turner.,2014). These technologies not only improve efficiency but also play a crucial role in addressing global challenges such as climate change, resource management, and sustainable development. A multi-physics coupling inversion framework is developed from multi-physics field coupling simulations. Through this approach, different geophysical datasets can be jointly inverted to produce three-dimensional subsurface models that agree with observations from multiple geophysical techniques.

Another significant application of penetrating remote sensing is oceanographic profile exploration. The use of oceanographic profiling sensors expands marine remote sensing from conventional two-dimensional monitoring to three- dimensional observation, enabling studies in areas such as biogeochemistry, marine ecology, ocean dynamics, and target detection. Nevertheless, the process involves addressing three major complex challenges.

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ISSN : 2583-0910
Agri-India TODAY
visit us at www.agriindiatoday.in

Peer reviewed
monthly newsletter

Article ID : 06/VI/58/0626

# MIDDLE EAST WAR AND INDIAN AGRICULTURE: ROLE OF LOW-COST INNOVATIONS

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## Abstract

Agriculture is undergoing rapid transformation due to climate change, rising input costs, labor shortages, and increasing pressure on natural resources. In this situation, low-cost agricultural innovations are emerging as practical solutions for improving productivity, profitability, and sustainability, especially for small and marginal farmers. Recent advances such as precision irrigation, solar-powered farm equipment, biofertilizers, integrated pest management, low-cost farm mechanization, digital advisory services, mobile-based applications, and climate-smart farming practices are helping farmers reduce production costs and enhance resource-use efficiency. These innovations promote efficient utilization of water, soil nutrients, energy, and labor while minimizing environmental degradation. Community-based approaches including Farmer Producer Organizations, custom hiring centres, and digital marketing platforms are further strengthening rural livelihoods. Government initiatives and technological advancements are accelerating the adoption of affordable agricultural technologies. The study concludes that low-cost innovations can play a significant role in achieving sustainable agriculture, climate resilience, food security, and improved farmers' income in developing countries like India.

**Keywords:** Low-cost innovations, sustainable agriculture, precision farming, digital agriculture, climate-smart farming, smallholder farmers, mechanization, natural farming.

## Introduction

Agriculture remains the backbone of the economy in many developing countries and supports the livelihoods of millions of rural families (FAO, 2022). In India, agriculture contributes significantly to employment, food security, and rural development. However, the agricultural sector faces multiple challenges, including declining soil fertility, erratic rainfall, increasing pest and disease incidence, rising labor wages, shrinking landholdings, and increasing production costs. Climate change has further intensified these problems by causing droughts, floods, heat stress, and irregular monsoon patterns (Subash & Ram Mohan, 2021).

Traditional agricultural practices often depend heavily on costly external inputs such as chemical fertilizers, pesticides, irrigation equipment, and machinery. Small and marginal farmers, who constitute the majority of Indian farmers, frequently lack the financial capacity to adopt expensive technologies. Therefore, there is a growing need for affordable, accessible, and sustainable innovations that can increase productivity while reducing production costs.

Recent advances in low-cost agricultural innovations are helping farmers address these challenges effectively (Gupta & Singh, 2021). These innovations include improved agronomic practices, precision farming tools, digital advisory systems, renewable energy applications, climate-resilient technologies, biological inputs, and low-cost farm machinery. Many of these innovations are based on local resources, indigenous knowledge, and farmer-led experimentation, making them highly adaptable to local conditions.

The integration of modern science with traditional wisdom has created new opportunities for sustainable agricultural development. Mobile phones, artificial intelligence, sensors, drones, and internet-based advisory systems are increasingly becoming affordable and accessible to rural communities. Simultaneously, practices such as organic farming, integrated pest management, crop diversification, mulching, and water harvesting are helping reduce dependence on expensive inputs. This paper examines the recent advances in low-cost innovations in agriculture and their significance in enhancing productivity, sustainability, profitability, and climate resilience.

### Importance of Low-Cost Innovations in Agriculture

Low-cost innovations are essential for improving the economic condition of small and marginal farmers. These technologies and practices enable farmers to achieve better yields with limited financial resources. Affordable innovations are particularly important in developing countries where access to institutional credit and modern infrastructure remains limited.

The major importance of low-cost agricultural innovations includes:

1. Reduction in production costs.
2. Improvement in crop productivity and quality.
3. Efficient use of water, nutrients, and energy.
4. Reduction in environmental pollution.
5. Increased resilience to climate change.
6. Enhanced profitability and farm income.
7. Promotion of sustainable agriculture.
8. Generation of rural employment opportunities.
9. Improved food and nutritional security.
10. Empowerment of women and youth in agriculture.

These innovations not only increase productivity but also strengthen ecological sustainability by reducing dependence on synthetic chemicals and fossil fuels (Pretty, 2018).

### Recent Advances in Precision Irrigation Technologies

Water scarcity is becoming one of the biggest challenges in agriculture. Traditional irrigation methods often lead to excessive water loss through evaporation, runoff, and deep percolation. Recent advances in low-cost precision irrigation technologies are helping farmers use water more efficiently.

**Drip Irrigation Systems:** Low-cost drip irrigation systems deliver water directly to the root zone of plants, reducing water wastage and improving crop growth. Government subsidies and locally manufactured components have made drip irrigation more affordable for small farmers. Bucket drip systems and gravity-based drip irrigation are especially useful for vegetable cultivation in small holdings.

**Sprinkler Irrigation:** Portable and mini sprinkler systems are increasingly used for field crops, vegetables, and orchards. These systems help save water and labor while improving irrigation efficiency.

**Solar-Powered Irrigation Pumps:** Solar irrigation pumps are becoming popular due to increasing fuel prices and unreliable electricity supply. Solar pumps reduce energy costs and promote clean energy use in agriculture. Recent innovations have reduced the cost of solar systems, making them accessible to small farmers through government support schemes.

**Soil Moisture Sensors:** Affordable soil moisture sensors connected to mobile applications help farmers irrigate crops according to actual water requirements. These sensors reduce unnecessary irrigation and improve water-use efficiency.

**Rainwater Harvesting Structures:** Farm ponds, check dams, rooftop harvesting systems, and recharge pits are low-cost water conservation structures that help farmers store rainwater for irrigation during dry periods.

These innovations contribute significantly to water conservation and climate-resilient agriculture (Singh & Verma, 2022).

### Advances in Soil Health and Nutrient Management

Soil fertility degradation is a major concern in intensive farming systems. Excessive use of chemical fertilizers has adversely affected soil structure, microbial activity, and long-term productivity. Recent low-cost innovations focus on restoring soil health through balanced nutrient management.

**Soil Testing and Soil Health Cards:** Portable soil testing kits and digital soil analysis systems enable farmers to assess nutrient status quickly and accurately. Soil Health Card programs provide recommendations for balanced fertilizer application, reducing unnecessary fertilizer use.

Integrated Nutrient Management combines organic manures, crop residues, biofertilizers, green manures, and chemical fertilizers in balanced proportions (Yadav *et al.*, 2020). This approach improves soil fertility while reducing input costs.

**Biofertilizers:** Biofertilizers such as Rhizobium, Azotobacter, Azospirillum, and phosphate-solubilizing bacteria are low-cost biological alternatives to chemical fertilizers. These microorganisms enhance nutrient availability and improve soil microbial activity.

**Vermicomposting:** Vermicomposting converts farm waste and organic residues into nutrient-rich compost using earthworms. It is an affordable technology that improves soil structure, water-holding capacity, and nutrient availability.

**Nano Fertilizers:** Recent advances in nano fertilizers, such as nano urea, help improve nutrient-use efficiency while reducing fertilizer consumption and environmental pollution.

**Crop Residue Recycling:** Instead of burning crop residues, farmers are increasingly adopting residue incorporation, mulching, and composting techniques to improve soil organic matter.

These innovations help reduce production costs while maintaining soil productivity and environmental sustainability.

### Low-Cost Innovations in Pest and Disease Management

Pests and diseases cause substantial crop losses worldwide. Excessive use of chemical pesticides increases production costs and creates environmental and health hazards. Recent advances emphasize eco-friendly and low-cost pest management approaches.

**Integrated Pest Management (IPM):** Integrated Pest Management combines cultural, biological, mechanical, and chemical control methods for sustainable pest management. IPM reduces pesticide use and improves ecological balance.

**Biopesticides:** Biopesticides derived from bacteria, fungi, viruses, and plant extracts are gaining popularity. Neem-based pesticides, Bacillus thuringiensis formulations, and Trichoderma products are affordable and environmentally safe.

**Pheromone and Sticky Traps:** Low-cost pheromone traps and yellow sticky traps help monitor and control insect populations without chemical sprays.

**Botanical Extracts:** Farmers increasingly use locally available botanical extracts such as neem seed kernel extract, garlic extract, chilli extract, and tobacco decoctions for pest control.

**Disease Forecasting Applications:** Mobile applications and weather-based forecasting systems help farmers predict pest and disease outbreaks, enabling timely preventive measures.

**Biological Control Agents:** Predators and parasitoids such as ladybird beetles, *Trichogramma,* and *Chrysoperla* are increasingly used in biological pest control programs.

These innovations reduce chemical dependency and promote environmentally sustainable crop protection.

### Advances in Digital Agriculture and Information Technology

Digital technologies are transforming modern agriculture by improving access to information, markets, and farm management tools. Affordable smartphones and internet connectivity have accelerated the spread of digital agriculture.

**Mobile-Based Advisory Services:** Farmers receive real-time information on weather forecasts, pest management, fertilizer recommendations, irrigation scheduling, and market prices through mobile applications and SMS services.

**Artificial Intelligence and Machine Learning:** Artificial intelligence-based tools help identify crop diseases, nutrient deficiencies, and irrigation requirements using smartphone images and sensor data.

**Drones in Agriculture:** Low-cost drones are increasingly used for crop monitoring, pesticide spraying, and nutrient application. Shared drone services through cooperatives and custom hiring centres are making drone technology accessible to small farmers.

**Internet of Things (IoT):** IoT-based systems integrate sensors, weather stations, and mobile applications to provide real-time farm management solutions.

**Digital Market Platforms:** Online agricultural marketing platforms connect farmers directly with buyers, reducing the role of intermediaries and improving price realization.

**E-Learning and Virtual Training:** Digital platforms and social media channels provide agricultural training, demonstrations, and expert guidance to rural farmers.

Digital agriculture improves decision-making, reduces production risks, and enhances agricultural efficiency (World Bank, 2021; Kumar & Sharma, 2020).

### Low-Cost Farm Mechanization Technologies

Labor shortages and rising wages have increased the importance of farm mechanization. However, large agricultural machinery is often unaffordable for small farmers. Recent advances focus on low-cost and small-scale mechanization.

**Power Weeders and Mini Tillers:** Portable power weeders and mini tillers are useful for small farms and reduce labor requirements significantly.

**Seed Drills and Planters:** Animal-drawn and manually operated seed drills improve sowing efficiency and ensure proper seed placement.

**Multi-Crop Threshers:** Small-scale multi-crop threshers help farmers reduce post-harvest losses and labor costs.

**Battery-Operated Sprayers:** Battery-operated sprayers are lightweight, energy-efficient, and reduce manual drudgery.

**Solar Dryers:** Low-cost solar dryers help farmers preserve fruits, vegetables, spices, and medicinal plants while reducing post-harvest losses.

**Custom Hiring Centres:** Custom hiring centres provide farm machinery on a rental basis, allowing small farmers to access modern equipment without purchasing costly machines.

Affordable mechanization improves timeliness of operations, labor productivity, and crop yields (Government of India, 2023).

### Organic Farming and Natural Farming Innovations

Growing concerns regarding soil degradation, environmental pollution, and food safety have increased interest in organic and natural farming systems.

**Natural Farming:** Natural farming promotes the use of locally available resources such as cow dung, cow urine, crop residues, and microbial cultures. This approach minimizes dependence on chemical fertilizers and pesticides.

**Jeevamrit and Beejamrit:** Jeevamrit and Beejamrit are microbial formulations prepared from cow dung, cow urine, pulse flour, jaggery, and soil. These low-cost inputs improve soil microbial activity and seed protection.

**Mulching Techniques:** Mulching conserves soil moisture, suppresses weeds, and improves soil temperature regulation.

**Crop Rotation and Diversification:** Crop rotation and intercropping reduce pest incidence, improve soil fertility, and increase farm income stability.

**Urban and Terrace Farming:** Low-cost urban farming technologies such as vertical gardens, rooftop cultivation, hydroponics, and kitchen gardens are gaining popularity.

Organic and natural farming systems contribute to environmental sustainability and reduce input costs.

### Climate-Smart Agricultural Innovations

Climate change is one of the greatest threats to agriculture. Climate-smart innovations help farmers adapt to changing climatic conditions while reducing greenhouse gas emissions.

**Climate-Resilient Crop Varieties:** Short-duration, drought-tolerant, flood-tolerant, and heat-resistant crop varieties help farmers cope with climatic stresses.

**Conservation Agriculture:** Conservation agriculture practices such as zero tillage, residue retention, and crop diversification improve soil health and moisture conservation.

**Agroforestry Systems:** Agroforestry integrates trees with crops and livestock to improve biodiversity, soil fertility, and carbon sequestration.

**Weather-Based Agro-Advisories:** Weather forecasting systems provide farmers with timely information regarding rainfall, temperature, and extreme weather events.

**Community Seed Banks:** Community-managed seed banks help preserve traditional climate-resilient crop varieties.
These innovations strengthen the resilience of farming systems under changing climatic conditions.

**Innovations in Livestock and Integrated Farming Systems**
Integrated farming systems combine crop production, livestock, fisheries, poultry, and agroforestry for efficient resource utilization.

**Azolla Cultivation:** Azolla is a low-cost protein-rich feed supplement for livestock and poultry.

**Hydroponic Fodder Production:** Hydroponic fodder systems produce green fodder using limited water and space.

**Biogas Plants:** Small biogas units convert animal waste into cooking fuel and organic slurry for crop production.

**Integrated Fish Farming:** Fish farming integrated with paddy cultivation increases farm productivity and income.
**Backyard Poultry:** Low-cost backyard poultry systems provide supplementary income and nutritional security.
Integrated farming enhances farm resilience, reduces waste, and improves resource recycling.

**Government Initiatives Supporting Low-Cost Agricultural Innovations**
Governments play an important role in promoting affordable agricultural technologies through subsidies, training, financial support, and institutional programs.

**Pradhan Mantri Krishi Sinchayee Yojana (PMKSY):** This scheme promotes efficient irrigation technologies such as drip and sprinkler irrigation.

**Soil Health Card Scheme:** The Soil Health Card Scheme encourages balanced fertilizer use based on soil testing.

**National Mission for Sustainable Agriculture (NMSA):** NMSA supports climate-resilient agricultural practices and water conservation technologies.

**Paramparagat Krishi Vikas Yojana (PKVY):** PKVY promotes organic farming and cluster-based organic agriculture.

**Sub-Mission on Agricultural Mechanization (SMAM**): SMAM supports affordable farm mechanization and custom hiring centres.

**Kisan Drone Initiative:** The government promotes the use of drones for precision agriculture and crop monitoring.

**Digital Agriculture Mission:** The Digital Agriculture Mission encourages digital technologies, data-driven agriculture, and smart farming solutions.

Government support is crucial for increasing awareness and adoption of low-cost innovations

(National Innovation Foundation, 2021).

**Challenges in Adoption of Low-Cost Agricultural Innovations**

Despite significant progress, several challenges limit the adoption of low-cost agricultural innovations.

**Lack of Awareness:** Many farmers are unaware of available technologies and scientific practices.

**Limited Access to Credit:** Small farmers often face difficulties in obtaining institutional credit for technology adoption.

**Inadequate Training:** Lack of technical knowledge and extension services restricts effective implementation.

**Poor Digital Connectivity:** Rural internet connectivity and digital literacy remain inadequate in many regions.

**Fragmented Landholdings:** Small and scattered landholdings limit mechanization and precision agriculture adoption.

**Initial Investment Costs:** Even low-cost technologies may require initial investments beyond the capacity of poor farmers.

**Market Uncertainty:** Price fluctuations and lack of assured markets discourage farmers from adopting innovative practices.

Addressing these challenges requires coordinated efforts from governments, research institutions, private companies, and farmer organizations.

**Future Prospects of Low-Cost Agricultural Innovations**

The future of agriculture depends largely on sustainable, affordable, and climate-resilient technologies. Emerging innovations are expected to further transform agriculture in the coming years.

**Expansion of Smart Farming:** Affordable sensors, automation tools, and artificial intelligence applications will become more accessible to small farmers.

**Renewable Energy Integration:** Solar-powered machinery, cold storage units, and irrigation systems will reduce energy costs and carbon emissions.

**Community-Based Innovation Models:** Farmer cooperatives, FPOs, and self-help groups will play an increasing role in technology dissemination.

**Precision Nutrient and Water Management:** Low-cost precision farming tools will improve input-use efficiency and sustainability.

**Increased Use of Biological Inputs:** Biological fertilizers and biopesticides will replace a significant portion of chemical inputs.

**Strengthening Digital Infrastructure:** Improved internet access and digital literacy will accelerate agricultural modernization.

**Climate-Smart Agriculture Expansion:** Climate-resilient farming systems will become essential for ensuring food security under changing environmental conditions (Zhao *et al.*, 2017).

Future agricultural development should focus on inclusive innovation models that benefit smallholders and protect natural resources.

## Conclusion

Recent advances in low-cost innovations in agriculture are transforming farming systems by improving productivity, profitability, sustainability, and climate resilience. Affordable technologies such as precision irrigation, biofertilizers, digital advisory systems, low-cost mechanization, integrated pest management, solar-powered equipment, and natural farming practices are helping farmers reduce production costs while increasing resource-use efficiency.

These innovations are especially important for small and marginal farmers who face financial and environmental constraints. The integration of scientific research, indigenous knowledge, renewable energy, and digital technologies has created new opportunities for sustainable agricultural development. Government support through subsidies, training programs, extension services, and policy initiatives has further accelerated the adoption of affordable technologies.

However, challenges such as lack of awareness, inadequate infrastructure, limited credit access, and poor digital connectivity still hinder widespread adoption. Therefore, strengthening agricultural extension systems, improving rural infrastructure, enhancing farmer training, and promoting community-based innovation models are essential.mLow-cost agricultural innovations offer a practical pathway for achieving sustainable food production, environmental conservation, and improved livelihoods. With continued research, policy support, and farmer participation, these innovations can play a crucial role in ensuring future agricultural sustainability and rural prosperity.

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ISSN : 2583-0910
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Article ID : 06/VI/59/0626

# BREEDING CLIMATE RESILIENT PIGEONPEA VARIETIES

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## Abstract

Pigeonpea [*Cajanus cajan* (L.) Millsp.] is an important pulse crop that is widely grown in rainfed and semi-arid regions due to its nutritional value. However, the growing impact of climate change, including rising temperatures, erratic rainfall, prolonged droughts, waterlogging, and emerging pest and disease pressures, poses a serious threat to pigeonpea production and global food security. This article discusses recent advances in pigeonpea improvement strategies aimed at increasing resilience to abiotic and biotic stress. Furthermore, emerging technologies such as genomic selection, high-throughput phenotyping, and genome editing are expected to further strengthen pigeonpea improvement programs. Integrating conventional breeding with advanced molecular tools will be critical in developing climate-smart pigeonpea varieties capable of maintaining productivity under changing environmental conditions.

**Keywords:** Pigeonpea, Climate resilience, genomic selection, abiotic stress, biotic stress

## Introduction

Pigeonpea [*Cajanus cajan* (L.) Millsp.] is a resilient crop (2n = 22) and nutrient-dense grain legume that can improve agricultural sustainability (Singh *et al*., 2020). It is a multipurpose crop that can be used for food, livestock feed, fodder, and domestic fuelwood, making it a viable crop for small and marginal farmers in resource-constrained rainfed environments (Saxena 2008). Pigeonpea seeds are extremely nutritious, containing 21-25% protein and high levels of essential amino acids, vitamins, minerals, and fiber. Pigeonpea is grown on 6.36 million hectares of land worldwide, with an annual yield of 5.48 million metric tons (FAO 2021).

Unfortunately, we have recently (2015-19) seen a global rise in average temperatures (by 0.2 °C) and atmospheric $CO2$ concentrations (by 20%) compared to the previous 5 years (2011-15) (WMO 2019). However, the rapid escalation of climate change endangers this staple food crop. Unpredictable monsoons, high temperatures, prolonged droughts, and waterlogging are testing the pigeonpea's physiological limits. For more than fifty years, traditional research struggled to make significant advances in pigeonpea yield, with average on-farm productivity globally only increasing from 707 kg/ha in 1970 to around 856 kg/ha recently (Saxena, 2026).

To ensure global food security, scientists are shifting away from traditional trial-and-error farming and toward "Smart Breeding." A new era of climate-ready pigeonpea varieties is emerging through the use of molecular genetics, advanced technology engineering, and environmental manipulation.

## Pigeonpea Improvement for Stress Resilience

Changing climate and cultivation practices necessitate a new approach to feeding the growing population. Among the various approaches to stress management, breeding for tolerance is regarded as the most effective strategy because it is both environmental and farmer-friendly, as well as durable. Thus, developing and deploying host plant resistance is an economically viable way to alleviate abiotic and biotic stress-associated yield losses in an evolving environment.

**Genetic Resources in Pigeonpea**

Pigeonpea is an important, often cross-pollinated grain legume crop with a genome size of 858 Mbp (Saxena *et al*.,2010), and it is the first legume crop to be sequenced by scientists from ICRISAT and other institutions (Singh *et al*., 2012). There are 11 related genera and thirty-two distinct species in the genus Cajanus. Nearly 13,632 accessions of Cajanus species from 74 countries are conserved in the ICRISAT gene bank. It consists of 555 wild relatives from 6 different genera and 57 species, 8215 landraces, 4795 breeding lines, and 67 improved cultivars (Upadhyaya *et al*., 2007, 2012).

**Pre-breeding**

Pre-breeding activities generally involve identifying desirable traits and then transferring them into an elite cultivar that can be further utilized to improve crops. The crop's wild relatives contain several beneficial genes that resist biotic and abiotic stresses. Pre-breeding aims to reduce genetic uniformity in crop species by utilizing distantly related wild relatives to improve crop yield, pest and disease resistance, and other quality characteristics (Shimelis and Liang 2012).

**Marker-Assisted Selection (MAS)**

MAS is a pioneering approach in modern breeding, allowing for the precise selection of desired traits based on genetic markers rather than observable phenotypes. The first step in marker-assisted selection (MAS) is to carefully map the genes or quantitative trait loci (QTL) of interest using advanced methods. Mapping populations derived from crossing contrasting parents is the most essential requirement for mapping the target genomic regions. Two RAPD markers (Kotresh *et al*., 2006), four SCAR markers (Prasanthi *et al*., 2009), and six SSR markers (Singh *et al*., 2013) were determined to be associated with Fusarium wilt resistance in pigeonpea. Six different QTLs for SMD resistance were identified, accounting for up to 24.72% of phenotypic variation and associated with linkage groups 7 and 9 (Gnanesh *et al*., 2011).

**Genomics-Assisted Breeding (GAB)**

The sequencing of the pigeonpea genome provided advanced molecular toolkits. Genomics-Assisted Breeding (GAB) enables scientists to avoid slow, visual field selections (Kole *et al*., 2015). GS calculates Genomic Estimated Breeding Values (GEBVs) using genome-wide marker data rather than individual genes (Sinha *et al*., 2021). This statistical modeling predicts how a breeding line will respond to climate stress before it ever experiences a field drought.

**Speed Breeding**

Due to the crop's long maturity period and sensitive photoperiod (day-length) response, traditional pigeonpea breeding cycles can take up to 7–10 years (Saxena *et al*., 2018). Breeders can harvest up to 4-6 generations annually rather than just one by using Speed Breeding facilities, where artificial lighting, temperature, and humidity are carefully controlled (Sinha *et al*., 2021).

**Breakthroughs in Climate-Resilient Pigeonpea Breeding**

1. **Breaking the Disease and Drought Barriers:**
   **ICP 8863 (Maruti):** The world's first extremely successful Fusarium wilt-resistant variety, Maruti was created as a benchmark achievement in disease resistance breeding (Kumar, 2024). It single-handedly supported the livelihoods of millions of smallholders in southern and central cultivation zones by preventing total crop loss during drought-stressed, wilt-prone seasons (Kumar, 2024).

**ICPL 87119 (Asha):** Widely regarded as a massive success in pulse breeding, Asha combined deep-rooted drought tolerance with dual resistance to Fusarium wilt and Sterility Mosaic Disease (SMD) (Kumar, 2024). This variety successfully protected farmers from the severe "green plague" that spreads during unusually warm years (Kumar, 2024).

2. **Beating the Heat**
   **ICPV 25444:** In a historic milestone for agricultural science, researchers at the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) officially unveiled ICPV 25444, the world's first highly heat-resilient, photo-insensitive, and thermo-insensitive pigeonpea cultivar (World Record Academy, 2025).

## Future prospects

The changing climate has subjected crop plants to a variety of biotic and abiotic stresses. Hence, yield and climate resilience traits in pigeonpea must be given equal weightage. Classical plant breeding has been significantly impacted by recent advancements in DNA sequencing technologies in the post-Mendelian era. The availability of high-throughput phenotyping platforms, combined with rapid generation advancement techniques, can accelerate the pace of pigeonpea crop improvement. DNA marker-assisted breeding methods such as MABC, MARS, GWAS, candidate gene identification, and GS have the potential to make a significant impact. Genetic engineering/genome editing tools can be used to target previously identified candidate genes for desired traits.

## Conclusion

Global agriculture is rapidly changing due to climate change, and the production of pigeonpeas is no exception. In this situation, it is now crucial to breed climate-resilient pigeonpea varieties in order to guarantee food and nutritional security, especially in rainfed and resource-poor farming systems. The development of superior pigeonpea cultivars with increased adaptability and yield stability has been accelerated by the successful identification and use of a variety of genetic resources, as well as developments in marker-assisted selection, genomics-assisted breeding, and speed breeding. The enormous potential of scientific innovation in tackling upcoming agricultural challenges is demonstrated by recent advances in climate-smart pigeonpea breeding. However, ongoing research on multi-stress tolerance, improved phenotyping, and precise genomic interventions is required due to the complexity of climate-associated stresses.

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ISSN : 2583-0910
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Peer reviewed
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Article ID : 06/VI/60/0626

# GUARDIANS OF THE GREEN CANOPY: UNVEILING THE ECOLOGICAL IMPORTANCE OF THE ASIAN WEAVER ANT, *Oecophylla smaragdina*

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## Abstract

Asian weaver ants (*Oecophylla smaragdina*) are known for their strange nest-building behavior. The workers use the silk produced by the larvae to build large and elaborate nests in trees. These ants are distributed in Southeast Asia and Australia. They have very altruistic social structures and are important for natural pest control, especially in agricultural areas. Their territorial and aggressive behaviour makes them effective at controlling pests that damage crops, which could bring potential benefits to sustainable farming. It has a complex colony structure with multiple queens. Colonies are territorial and complex communication through pheromones and tactile signals. Their extracts and pheromones from the body have antimicrobial and repellent properties. Chemical signals for maintenance of large foraging areas.

**Keywords:** Agriculture, Nest Building, *Oecophylla smaragdina*, Silk Production.

## Introduction

The Asian Weaver Ant *Oecophylla smaragdina* (Fabricius, 1775), is far from being an ordinary insect, these ants are amazing for their intelligence, cooperation and ecological importance. They are found throughout India, Southeast Asia and northern Australia where they are strictly arboreal. But what sets them apart is that they use silk spun by their larvae to sew leaves together into elaborate nests. Feared for their painful bite, they are excellent natural pest controllers and valuable allies in agriculture. *O. smaragdina* knowledge provides insights into sustainable agriculture, social insect behaviour and biomimetic design for swarm robotics. Traditionally used for bio-control in Southeast Asia and India. Reduces pesticide use, improves crop yield and fruit quality. Also used in some areas for food and medicinal purposes.

**Bionomics:** The Asian weaver ant has a complete metamorphosis, passing through egg, larva, pupa and adult stages (Figure 1). The egg stage lasts 1-2 weeks, the larval stage lasts 3-4 weeks, the pupal stage lasts 1-2 weeks, and adult workers live several months. The queen lays eggs inside leaf nests. Asian weaver ants lay 100-300 eggs/day, 30000-100000 eggs/year. where workers protect and nurture the young. The pupae then develop into adults which continue to develop into workers, males, or queens. Colonies are large, well organized, and sometimes contain thousands of individuals in many nests on the same tree.

**Silk secretion and nest construction:** The silk is secreted by the salivary glands of the larvae. The glands produce a fibroin-type silk protein that becomes a thread when exposed to air. The worker ant collects the leaf around and weaves with the help of silk. The finished nest is usually a hanging structure attached with several leaves. The silk holds the leaves together and folded into a compact shape, providing a stable, protective home for the colony.

**Morphology:** The Asian weaver ant has a slim body that can be reddish-orange to greenish in color, well suited to life in trees. Its head has strong mandibles used for biting, carrying prey and building nests. The antennae are very sensitive, elbowed and help in communication and navigation. The thorax is long and flexible to allow movement during leaf weaving (Figure 2). Their long, powerful legs enable them to move efficiently over the branches. One of the most interesting things is the workers ability to build living chains, pulling the leaves together to make nests. One of the most obvious features of the Asian weaver ant is the presence of spines on the thorax, especially the pronotum which is somewhat flattened and angular. The spines are often lateral and very distinct from many other ant species. The spines are 100-300 micrometers.

**Host Range:** Asian weaver ants are generalist predators and are found on many tree crops such as mango, coconut, citrus, cashew, cocoa, guava, sapota, arecanut, oil palm, tea, coffee etc. They feed on leafhoppers, fruit flies, mealy bugs, scale insects, grasshopper nymphs, weevils and fruit borers. They are predatory and have a wide range of hosts. This makes them very good in agricultural ecosystems as they naturally reduce pest populations.

Figure 1. Physiological properties of the visual system in the green weaver ant, *Oecophylla smaragdina* (Ogava *et al.,* 2023)

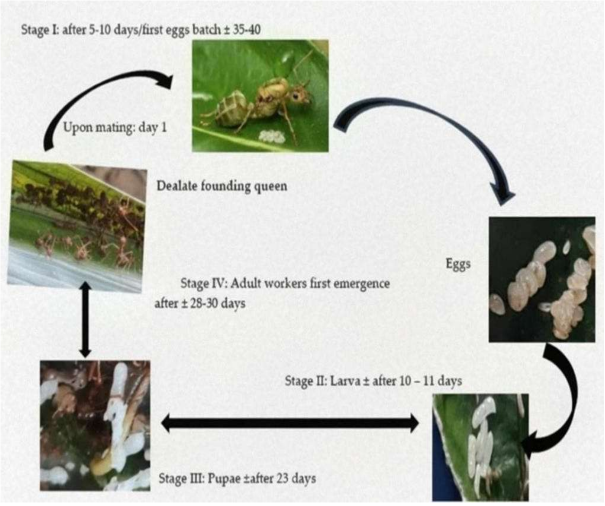

Figure 2. *Oecophylla smaragdina* life cycle chronological stages at 30ºC (Pierre *et al.,* 2022)

**Pest Management:** The Asian weaver ant is an important component of environmentally-sound pest management. They work better when tree canopies are connected and it's easy to get around. Not using too many pesticides helps keep their numbers up. Farmers sometimes relocate nests to make artificial bridges for colony spread. These ants are natural predators of aphids, whiteflies, grasshopper nymphs and fruit borers which reduces the pest damage by about 50-70 % and crop yield is improved by 20-30 % in crops like citrus, coconut, coffee, tea and arecanut. But by using chemicals carefully so as not to hurt these useful insects.

## Conclusion

The Asian weaver ant is one of nature's effective agents of pest control. Although these ants are aggressive and their sting can be painful, they play an important role in agriculture and the environment. They help farmers by naturally controlling many crop pests, which reduces the need for chemical pesticides. Because of this, they are considered useful in sustainable farming practices. Studying the behavior and ecological role of Asian weaver ants can help in managing pest problems and improving yield in different plantation crops. Their use in agriculture not only supports eco-friendly farming but also helps in reducing excessive pesticide application.

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ISSN : 2583-0910
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Article ID : 06/VI/61/0626

# SMART LOW-COST TECHNOLOGIES SECURING FARMERS' INCOME IN TIMES OF GLOBAL CRISIS

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## Abstract

Global crises driven by geopolitical conflicts, climate change, rising fuel and fertilizer prices, and market disruptions are creating major challenges for Indian agriculture, particularly for small and marginal farmers. Increasing input costs and climate variability are reducing farm profitability and sustainability. In this context, smart low-cost agricultural technologies are emerging as practical solutions for improving farmers' income and resilience. This paper highlights affordable innovations such as precision irrigation, soil health management, mobile-based advisory services, solar-powered equipment, integrated nutrient and pest management, digital marketing platforms, crop diversification, and climate-smart farming practices in India. These technologies help reduce cultivation costs, improve productivity, enhance resource-use efficiency, conserve natural resources, and minimize risks from market and climate uncertainties. The paper emphasizes their importance in ensuring sustainable farm income, food security, and rural livelihood improvement in India.

## Introduction

Indian agriculture is currently facing a complex combination of global and domestic challenges. Rising population pressure, shrinking agricultural land, climate change, increasing production costs, depletion of natural resources, and unstable market conditions have already placed heavy stress on the farming sector. In addition, ongoing global conflicts, particularly tensions in the Middle East, have disrupted international supply chains of fuel, fertilizers, and agricultural inputs, leading to sharp increases in input prices and uncertainty in fertilizer availability. In this global crisis scenario, sustaining farmers' income in India while reducing cultivation costs has become a national priority. Low-cost agricultural technologies are emerging as practical and sustainable solutions for Indian farmers. These technologies focus on maximum utilization of locally available resources and minimum dependence on costly external inputs. They help achieve higher productivity, improved crop quality, efficient resource conservation, and long-term agricultural sustainability.

Technologies such as integrated nutrient management, organic farming, seed treatment, crop diversification, micro-irrigation, conservation agriculture, integrated pest management, biofertilizers, and small-scale farm mechanization will play a vital role in strengthening farm resilience and increasing income, especially for India's small and marginal farmers. This paper highlights important low-cost agricultural technologies that can help Indian farmers achieve higher production and profitability under present global uncertainties. It will serve as a useful guide for farmers, agricultural students, and agricultural development professionals.

## Current Status and Challenges of Indian Agriculture

India is an agrarian country where a large population depends directly or indirectly on agriculture for livelihood, food security, and rural employment. Agriculture remains the backbone of the national economy, but the sector is currently facing severe challenges due to both domestic pressures and global crises. Rising costs of fertilizers, pesticides, diesel, labor, irrigation, and farm machinery are continuously reducing farmers' profitability. At the same time, unstable market prices often fail to provide farmers with remunerative returns for their produce.

Climate change has added another major challenge. Irregular rainfall, droughts, floods, hailstorms, heat waves, and rising temperatures are adversely affecting crop productivity and farm stability. Moreover, agricultural landholdings are continuously shrinking, and the majority of Indian farmers belong to small and marginal categories with limited financial resources.

The present global geopolitical situation, especially conflicts in the Middle East and disruptions in international trade routes, has further aggravated the crisis by affecting the supply and prices of fuel, fertilizers, and other agricultural inputs. India's dependence on imported fertilizers such as urea, DAP, and potash has increased concerns regarding input availability and affordability.

India imports both raw materials and finished fertilizers to meet its agricultural demand. Major imported raw materials include rock phosphate, phosphoric acid, ammonia, sulphur, and natural gas used for fertilizer manufacturing. India also imports finished fertilizers such as urea, Di-Ammonium Phosphate (DAP), Muriate of Potash (MOP), and complex NPK fertilizers. Since India has limited reserves of potash and phosphate minerals, dependence on imports remains high, especially for phosphatic and potassic fertilizers. Major supplier countries include Russia, Saudi Arabia, Morocco, Jordan, Canada, China, Qatar, and Oman.

Under these circumstances, low-cost agricultural technologies have emerged as a practical and sustainable solution. Techniques such as integrated nutrient management, organic farming, crop diversification, micro-irrigation, conservation agriculture, biofertilizers, and farm mechanization can help farmers reduce costs, conserve natural resources, and improve productivity. Adoption of locally suitable scientific technologies can make Indian agriculture more resilient, profitable, and sustainable during global uncertainty.

**Smart low-cost agricultural technologies**

In the present global crisis situation, low-input agricultural technologies have become highly important for Indian agriculture. Low-cost technologies help farmers achieve higher productivity with lower investment while conserving natural resources. These technologies are especially beneficial for small and marginal farmers who have limited capital and resources. Practices such as organic farming, biofertilizers, local seed conservation, natural farming, crop residue management, and integrated nutrient management reduce dependence on costly external inputs and make farmers more self-reliant. They also improve soil health, water conservation, and environmental sustainability.

**1. Crop Planning and Scientific Agricultural Management:** Scientific crop planning is essential for profitable and sustainable agriculture during global uncertainty. Farmers should select crops according to soil type, climate, irrigation facilities, and market demand to reduce risks and increase income. Unplanned cultivation often increases production costs and lowers profitability. Crop rotation, improved varieties, balanced fertilization, timely irrigation, and season-based crop selection during *Kharif, Rabi,* and *Zaid* help maintain soil fertility and reduce pest and disease incidence. Market-oriented farming also provides better returns. Farmers can include vegetables, pulses, spices, medicinal, and other cash crops along with traditional cereals to generate higher income from smaller landholdings. Diversified farming systems also reduce the risk of crop failure under adverse climatic conditions.

**2. Quality Seeds and Seed Treatment:** Quality seeds are the foundation of higher crop production. The use of certified and climate-resilient varieties improves germination, crop growth, and yield while reducing pest and disease attack. Seed treatment is a simple, low-cost, and eco-friendly technique that protects crops from seed-borne diseases and improves plant vigour. Treatment with biofertilizers and bioagents such as *Trichoderma*, *Rhizobium*, *Azotobacter*, and PSB enhances nutrient availability and crop health. Scientific studies show that seed treatment can increase yields by 10–20 percent in rice, wheat, pulses, and oilseed crops.

**3. Importance of Timely Sowing and Row Sowing:** Timely sowing and row planting are key components of scientific farming. Crops sown at the proper time receive favourable temperature, moisture, and sunlight, leading to better germination and higher productivity. Row sowing ensures proper plant spacing, efficient nutrient use, easier weed control, and reduced seed requirement. Modern methods such as zero tillage, seed drills, and mechanical transplanting reduce labor and irrigation costs while increasing yields. Scientific evidence shows that timely sowing and row planting can increase crop productivity by 10–25 percent, particularly in rice, wheat, and pulse crops in Uttar Pradesh.

**4. Use of Organic Fertilizers and Compost:** In the present global crisis, rising fertilizer prices and disruptions in international supply chains have increased the importance of organic fertilizers in Indian agriculture. Reduced availability and higher costs of imported fertilizers such as urea, DAP, and potash have encouraged the use of economical and sustainable alternatives like farmyard manure, vermicompost, NADEP compost, green manure, and crop residues. These organic sources improve soil structure, water-holding capacity, microbial activity, and nutrient availability while maintaining long-term soil fertility and reducing cultivation costs.

Vermicomposting is one of the most effective low-cost technologies. Earthworms such as *Eudrilus eugeniae* and *Perionyx excavatus* convert cow dung, crop residues, and farm waste into nutrient-rich compost within 45–60 days. Vermicompost contains essential nutrients and micronutrients that improve soil health, crop quality, and productivity in cereals, vegetables, and fruit crops. It also creates employment opportunities for farmers, rural youth, and women, supporting sustainable agriculture and higher farm income during global uncertainty.

**5. Importance of Green Manure and Legume Crops:** Green manure and legume crops are economical and eco-friendly methods for improving soil fertility and reducing fertilizer dependence. Crops such as *dhaincha* (*Sesbania*), sunnhemp, mung bean, and black gram increase soil organic carbon and nitrogen when incorporated into the field. They also improve soil structure, water retention, and the availability of potassium, sulphur, and micronutrients. As a result, fertilizer costs decrease while crop productivity and profitability improve. Green manuring can save 50- 80 kg N in rice with positive residual impact on succeeding wheat crop rice-based systems.

Legume crops play a special role in sustainable agriculture because they fix atmospheric nitrogen through *Rhizobium* bacteria present in their root nodules. Inclusion of pigeon pea, mung bean, black gram, and other pulses in crop rotations naturally enriches soil fertility and benefits succeeding crops. Crop residue incorporation after harvest further improves soil organic matter and nutrient recycling.

In the present global situation, dependence on imported fertilizers has become a serious concern for Indian agriculture. Supply disruptions and rising transportation costs have increased fertilizer prices, creating uncertainty for farmers. Therefore, greater emphasis must be given to green manuring, composting, biofertilizers, crop residue management, biogas slurry, micronutrients, water-soluble fertilizers, and nano fertilizers. Adoption of these low-cost technologies can help farmers reduce external input dependence and make agriculture more resilient, profitable, and environmentally sustainable.

**6. Soil Testing and Soil Health Management:** Soil health is the foundation of sustainable and profitable agriculture. Continuous cultivation, imbalanced fertilizer use, soil erosion, and residue burning have reduced soil fertility in many parts of India. Deficiencies of organic carbon, nitrogen, phosphorus, potash, zinc, sulphur, and boron are increasing, especially in intensively cultivated regions. In the present global fertilizer crisis, soil testing and balanced nutrient management have become essential for reducing input costs and improving fertilizer-use efficiency.

The Soil Health Card Scheme promotes scientific nutrient management by helping farmers identify nutrient deficiencies and apply fertilizers according to crop requirements. However, many soil testing laboratories face challenges such as inadequate infrastructure, shortage of skilled staff, outdated equipment, delayed testing, and limited access for small farmers. Strengthening laboratory infrastructure, updating fertilizer recommendations, digitalization, and timely advisory services are essential for improving soil health, farm productivity, and climate-resilient agriculture in India.

**7. Integrated Nutrient Management:** Integrated nutrient management is a scientific agricultural practice that involves involves the balanced use of nitrogen, phosphorus, and potash fertilizers along with manure, compost, vermicompost, green manure, and crop residues. Biofertilizers such as Rhizobium, Azotobacter, and PSB are also used. Balanced use of micronutrients such as zinc, sulfur, and boron also plays an important role in increasing crop productivity. Applying fertilizers based on soil testing reduces unnecessary expenditure and increases nutrient utilization efficiency.

Integrated nutrient management increases soil organic carbon, improves water holding capacity, and improves the availability of micronutrients. This increases both crop production and quality. This technique is considered crucial for reducing dependence on chemical fertilizers, protecting the environment, and promoting sustainable agricultural development. Integrated nutrient management helps farmers achieve quality produce at lower costs.

**8. Micro-irrigation techniques:** Water scarcity is a major problem in Indian agriculture. Micro-irrigation techniques such as drip and sprinkler irrigation are effective ways to increase water use efficiency. These techniques allow irrigating larger areas with less water. Drip irrigation delivers water directly to the roots of plants, which saves water and reduces weed growth. Drip irrigation has proven extremely beneficial for crops such as vegetables, fruits, and sugarcane. Sprinkler irrigation is suitable for shallow soil and uneven areas. It reduces irrigation costs and saves labor.

**9. Rainwater Harvesting and Water Conservation:** Most agriculture in India is dependent on rainfall. Therefore, rainwater harvesting and water conservation techniques are of particular importance. Rainwater can be conserved through techniques such as farm ponds, bunding contour bunding, and mulching.

Mulching conserves soil moisture and helps control weeds. Leaving crop residues in the field maintains soil temperature and increases organic matter. Water conservation techniques protect crops even during drought and reduce irrigation costs. This stabilizes farmers' income.

**10. Low-cost weed management techniques:** Weeds compete with crops for nutrients, water, and light, significantly reducing yields. Farmers often overspend on weed control, increasing costs. Low-cost weed management techniques (timely weeding, mulching, and crop rotation) are beneficial for farmers.

Using mechanical weeders in crops like rice and wheat reduces labor costs. Selective herbicides can be used in a limited and scientific manner when necessary. Using chemicals such as pendimethalin, bispyribac sodium, and 2,4- D in appropriate doses provides effective control. Integrated weed management reduces production costs and increases crop productivity.

**11. Integrated Pest and Disease Management:** Excessive use of chemical pesticides increases production costs and causes environmental pollution. Integrated Pest and Disease Management is an effective technique for low-cost pest control. In this method, importance is given to biological control, pheromone traps, light traps, neem-based insecticides and balanced fertilizer use. Pest infestation can be controlled in the initial stages by regular monitoring of the field. Biological agents like Trichogramma, Bacillus and Verticillium are useful in pest control. Use of neem cake and neem oil has also proved effective in pest control. Integrated management reduces expenditure on chemical medicines and results in safe production.

**12. Chemical-free pest, disease, and weed management:** Natural farming methods are gaining importance for safe, low-cost, and sustainable agriculture. Organic solutions prepared from cow urine, neem, garlic, and chili effectively control sucking pests, while border crops such as marigold, sunflower, basil, and cowpea attract beneficial insects and reduce pest infestation. Biological agents like *Trichoderma*, *Pseudomonas*, *Trichogramma*, and *Bacillus* help manage diseases and pests naturally. Removal of infected plants, crop rotation, intercropping, and mechanical weeding are also effective practices for disease and weed management.

The Government of India promotes chemical-free farming through schemes such as the *Traditional Agricultural Development Scheme* and the *Indian Natural Farming System*. These programs encourage the use of *Jeevamrit, Beejamrit, Neemastra,* and *Brahmastra*. Under Integrated Pest Management (IPM), farmers are trained in the use of pheromone traps, light traps, neem-based biopesticides, and eco-friendly weed management practices.

**13. Crop diversification and intercropping for climate resilient farming:** Climate change, irregular rainfall, drought, floods, and rising temperatures are seriously affecting agricultural production. In this situation, crop diversification and intercropping have emerged as effective climate-resilient farming practices. Crop diversification encourages farmers to grow cereals, pulses, oilseeds, vegetables, fruits, and fodder crops instead of depending on a single crop. This improves resource use efficiency, maintains soil fertility, reduces market risks, and provides multiple income sources. If one crop fails or prices decline, other crops ensure economic security for farmers.

Intercropping involves growing two or more crops together in a fixed row proportion to maximize the use of land, water, nutrients, and sunlight. Systems such as maize + pigeon pea, sugarcane + mustard, millet + mung bean, and coconut + vegetables provide higher productivity and profitability. Intercropping with pulses improves soil nitrogen and fertility naturally. These practices also reduce pest and disease incidence, stabilize production, and support sustainable, profitable, and climate-resilient agriculture.

**14. Income Enhancement through Small Agriculture-Based Enterprises:** In the present global crisis marked by rising input costs, climate uncertainty, and market fluctuations, small agriculture-based enterprises are emerging as effective low-cost solutions for increasing farmers' income. Allied activities such as dairy farming, goat rearing, poultry farming, beekeeping, mushroom cultivation, fish farming, vermicompost production, and food processing provide regular income and year-round employment opportunities for rural families.

Dairy farming ensures daily cash income through milk production, while animal waste can be used for organic manure and biogas. Goat rearing and poultry farming are suitable for small and marginal farmers due to low investment and quick returns. Beekeeping increases income through honey production and improves crop pollination. Mushroom cultivation is highly profitable because of its short production cycle and low space requirement.

Value addition through processing fruits, vegetables, spices, pickles, *papad,* and jams creates self-employment opportunities, especially for rural women and youth. These enterprises strengthen the rural economy, reduce migration, and promote sustainable and resilient agriculture.

**15. Self-Help Groups and Rural Women Empowerment:** Self-help groups (SHGs) have emerged as powerful instruments for the economic and social empowerment of rural women. Through collective savings, credit access, training, and group-based enterprises, women are becoming financially independent and contributing significantly to household income. SHGs are especially important during periods of economic instability and rising unemployment caused by global crises.

Women associated with SHGs are actively involved in dairy farming, goat rearing, poultry farming, mushroom cultivation, beekeeping, vermicompost production, food processing, tailoring, and handicrafts. Rural women are earning additional income through preparation of pickles, *papads*, spices, jams, and other household products. Collective production and marketing reduce costs and help ensure better prices for products.

SHGs also improve women's leadership capacity, self-confidence, and social awareness. Access to bank credit, government schemes, and skill-development programs enables women to establish small enterprises and strengthen family livelihoods. These groups are playing a major role in employment generation, poverty reduction, and rural development.

**16. Agricultural Startups and Rural Entrepreneurship:** Agriculture-focused startups are creating new opportunities for increasing farmers' income and modernizing Indian agriculture amid climate risks, rising input costs, and market uncertainty. These startups provide low-cost solutions such as improved seeds, soil testing, weather forecasting, drone spraying, farm mechanization, irrigation management, pest control, and digital crop advisory services. Many also connect farmers directly with consumers through online platforms, reducing middlemen and ensuring better prices. Startups involved in processing fruits, vegetables, dairy products, mushrooms, honey, and organic produce are generating employment opportunities for rural youth and women. Enterprises related to vermicompost production, agricultural waste management, and organic farming are further promoting sustainable agriculture, environmental conservation, and rural entrepreneurship.

**17. Increased Income through Digital Technologies in Crop Production:** Digital technologies are making agriculture more scientific, efficient, and profitable amid rising input costs, labor shortages, and climate uncertainty. Mobile phones, internet-based advisory services, drones, sensors, artificial intelligence, and digital platforms are helping farmers improve crop management at lower costs. Mobile-based services provide timely information on weather, improved seeds, fertilizers, pest management, and market prices, enabling better farm decisions. Drone technology supports rapid crop monitoring and precise spraying, reducing labor and chemical expenses. Sensor-based precision farming helps monitor soil moisture and nutrients for efficient irrigation and balanced fertilizer use. Digital platforms such as e-NAM connect farmers directly with markets, reducing middlemen and ensuring better prices. Overall, digital agriculture minimizes production risks, improves productivity and crop quality, and sustainably enhances farmers' income and resilience during global crises.

**Government Initiatives and Schemes:**

Government schemes play a crucial role in promoting smart low-cost agricultural technologies for sustainable farm income, especially during global crises marked by rising input costs, climate change, market instability, and supply-chain disruptions. In India, schemes such as the *Pradhan Mantri Krishi Sinchai Yojana* (PMKSY), *Digital Agriculture Mission, Soil Health Card Scheme, PM-KUSUM, e-NAM,* and *National Mission on Sustainable Agriculture* encourage farmers to adopt affordable and climate-smart technologies. These initiatives support precision irrigation, solar-powered farm equipment, soil testing, digital advisory services, organic farming, and efficient nutrient and pest management practices. Financial assistance, subsidies, training, and access to digital platforms help small and marginal farmers reduce production costs and improve productivity. Government support for *Farmer Producer Organizations* (FPOs), agricultural mechanization, storage, and value addition further strengthens market access and income opportunities. Such schemes enhance resilience, promote sustainable resource use, ensure food security, and improve rural livelihoods during periods of global economic uncertainty. Given below are different schemes:

**1. Pradhan Mantri Krishi Sinchayee Yojana (PMKSY):** The Pradhan Mantri Krishi Sinchai Yojana (PMKSY), campaigns like *"Water for Every Farm"* and *"More Crop per Drop"* are being implemented. Through these initiatives, micro-irrigation, farm ponds, drip and sprinkler irrigation are being encouraged.

Under the *"Jal Shakti Abhiyan,"* rainwater harvesting, pond rejuvenation, check dam construction, and groundwater recharge are being promoted. Thousands of water structures have been constructed and revived in rural areas under the *Amrit Sarovar Yojana*, improving irrigation and water conservation.

Through the MNREGA scheme, large-scale works related to bunding, farm ponds, drainage, and water conservation are being carried out. Additionally, under the *Atal Groundwater Scheme*, special emphasis is being placed on groundwater management and increasing water use efficiency.

These efforts are yielding positive results in water conservation, agricultural production stability, and

**2. Soil Health Card Scheme:** Soil Health Card Scheme encourages balanced fertilizer use through soil testing and nutrient recommendations. This scheme helps farmers reduce unnecessary fertilizer application, lower production costs, and maintain long-term soil fertility and productivity.

**3. Paramparagat Krishi Vikas Yojana (PKVY):** *Paramparagat Krishi Vikas Yojana* promotes organic farming, composting, biofertilizers, vermicompost, and natural farming practices. The scheme encourages farmers to adopt low-input sustainable agriculture and reduce dependence on chemical fertilizers and pesticides.

**4. National Mission on Sustainable Agriculture (NMSA):** *National Mission on Sustainable Agriculture* focuses on climate-resilient farming, integrated nutrient management, rainwater conservation, agroforestry, and soil health improvement. It supports sustainable technologies suitable for small and marginal farmers.

**5. Sub-Mission on Agricultural Mechanization (SMAM):** Sub-*Mission on Agricultural Mechanization* provides subsidies for low-cost farm machinery such as seed drills, zero-tillage machines, planters, weeders, and crop residue management equipment. Mechanization reduces labor costs and improves efficiency.

**6. National Food Security Mission (NFSM):** National Food Security Mission supports the production of rice, wheat, pulses, and oilseeds through improved seed distribution, integrated pest management, biofertilizers, and scientific crop management practices.

**7. PM-KUSUM Scheme:** PM-KUSUM Scheme promotes solar-powered irrigation pumps and renewable energy in agriculture. This reduces farmers' dependence on diesel and lowers irrigation costs during periods of rising global fuel prices.

**8. National Mission on Natural Farming:** *National Mission on Natural Farming* encourages cow-based natural farming, use of local inputs, bio-enhancers, and chemical-free cultivation practices. It aims to make farming self-reliant and environmentally sustainable.

**9. Rashtriya Krishi Vikas Yojana (RKVY):** *Rashtriya Krishi Vikas Yojana* supports innovative agricultural projects, integrated farming systems, value addition, and climate-smart technologies at the state level to improve productivity and farm income.

**10. National Rural Livelihoods Mission**: National Rural Livelihoods Mission is the major government initiative supporting women SHGs through training, savings promotion, and bank linkage programs.

*Lakhpati Didi Yojana:* Under the *Lakhpati Didi Yojana,* rural women are encouraged to establish agriculture-based enterprises and increase annual income through dairy, food processing, mushroom cultivation, and livestock-based activities.

*Stand-Up India Scheme and Pradhan Mantri Mudra Yojana:* Women entrepreneurs are also receiving financial assistance through *Stand-Up India Scheme* and *Pradhan Mantri Mudra Yojana*. These initiatives are helping rural women establish self-employment ventures and strengthening the rural economy.

**11. Promotion of Nano Fertilizers and Biofertilizers:** The government is promoting Nano Urea, Nano DAP, biofertilizers, micronutrients, and integrated nutrient management to reduce fertilizer consumption and improve nutrient-use efficiency during the global fertilizer crisis. These schemes collectively promote low-cost, resource-efficient, and environmentally sustainable technologies that can help Indian farmers remain resilient and profitable during global economic and geopolitical uncertainty.

## Summary and Conclusions

Global crises caused by climate change, geopolitical conflicts, rising fuel and fertilizer prices, and market instability have created serious challenges for Indian agriculture and farmers' livelihoods. In this context, smart low-cost agricultural technologies have emerged as practical solutions for sustaining farm income, especially for small and marginal farmers. Technologies such as precision irrigation, soil testing, integrated nutrient and pest management, organic farming, crop diversification, digital agriculture, and solar-powered equipment help reduce production costs, improve productivity, conserve resources, and strengthen climate resilience.

Digital platforms, agricultural startups, and Farmer Producer Organizations (FPOs) are improving market access and income opportunities. Government schemes such as PMKSY, PM-KUSUM, Soil Health Card Scheme, Digital Agriculture Mission, and e-NAM are promoting affordable climate-smart technologies. The study concludes that wider adoption of farmer-friendly and resource-efficient technologies can make Indian agriculture more resilient, profitable, sustainable, and self-reliant during global uncertainty.

ISSN : 2583-0910
**Agri-India TODAY**
visit us at www.agriindiatoday.in

Peer reviewed
monthly newsletter

Article ID : 06/VI/62/0626

# REWIRING EVOLUTIONARY GLITCH OF RuBisCO: BIOENGINEERING PHOTOSYNTHESIS FOR ENHANCED CROP YIELD POTENTIAL

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## Abstract

Photosynthetic inefficiency remains a major constraint on crop productivity, driving efforts to enhance carbon capture through bioengineering. This overview summarizes key strategies developed through the RIPE project and related studies to improve photosynthetic efficiency in crops. Major approaches include stabilizing RuBisCO assembly via the RAF1 chaperone, accelerating recovery from non-photochemical quenching, and redesigning carbon recycling through synthetic biology. It also highlights synthetic photorespiratory bypasses, advanced CCM, encapsulin-based systems, and engineering of C4-like leaf anatomy. These interventions have produced significant gains, including enhanced RuBisCO accumulation, improved carboxylation efficiency, biomass increases of up to 40% in tobacco, and yield improvements exceeding 20% in soybean. Modeling studies further suggest that $CO_2$-concentrating systems could increase yields in C3 crops by up to 60%. Collectively, these findings demonstrate the potential of photosynthesis engineering to improve crop yield, resource-use efficiency, and climate resilience.

**Keywords:** Molecular, C4 Rice, CRISPR, Plant Physiology, Synthetic biology

## Introduction: The Solar Energy Conversion Crisis

Although solar radiation is abundant, photosynthesis in crops remains surprisingly inefficient, with most plants converting less than 5% of received sunlight into usable biomass. This limitation results from ancient evolutionary trade-offs in carbon capture and processing rather than a biological design flaw. Today, such inefficiency has become a major bottleneck to global food security, as food production must increase by 50-70% to support a projected population of nearly 10 billion by 2050.

For decades, crop improvement relied mainly on traditional breeding approaches such as enhancing plant architecture, disease resistance, and harvest index. However, these methods are approaching their biological limits. Consequently, researchers are now focusing on directly engineering photosynthesis itself to improve crop productivity and agricultural sustainability.

## Evolutionary bottleneck in RuBisCO

RuBisCO (ribulose-1,5-bisphosphate carboxylase/oxygenase) is the most abundant protein on Earth and the primary entry point for inorganic carbon into the food chain. Despite its essential role, it has long been regarded as a biological paradox because it functions with remarkably low efficiency compared to most other enzymes. This inefficiency arises from both its structural complexity and inherent catalytic limitations.

RuBisCO is a massive 16-subunit enzyme that requires the coordinated action of more than 12 specialized partner proteins for proper assembly. In nearly 20% of catalytic reactions, the enzyme mistakenly binds $O_2$ instead of $CO_2$, generating toxic glycolate. Plants must recycle this compound through the energy-intensive process of photorespiration, which involves metabolite transport across the chloroplast, peroxisome, and mitochondrion. This process significantly reduces photosynthetic efficiency and global crop productivity.

To address these evolutionary limitations, the Realizing Increased Photosynthetic Efficiency (RIPE) project was established as a multi-institutional initiative focused on improving photosynthetic performance. Its primary objective is to enhance crop yield and global food security by targeting RuBisCO inefficiency and the slow relaxation of photoprotective mechanisms.

Recent bioengineering efforts are now addressing these limitations. Researchers have identified a critical chaperone that co-evolved with RuBisCO, RAF1 (RuBisCO Accumulation Factor 1). Providing RuBisCO with a modified and complementary version of RAF1, the accumulation of RuBisCO was successfully found to be doubled, which markedly boosted carboxylation efficiency and accelerated overall plant growth. There are various other strategies that researchers opted to enhance the yield, as follows:

### Strategy I: Relaxing Photoprotection

Plants have evolved a protective mechanism called Non-Photochemical Quenching (NPQ), which dissipates excess solar energy as heat to prevent leaf bleaching. However, this mechanism is kinetically slow and does not deactivate immediately when light intensity decreases. As a result, plants continue wasting energy as heat for several minutes instead of utilizing the available light for carbon fixation, leading to photosynthetic losses of 7.5–30%. To overcome this limitation, researchers from the RIPE project engineered the VPZ construct by overexpressing three genes: Violaxanthin de-epoxidase (V), Zeaxanthin epoxidase (P), and PSII subunit S (*Z/PsbS*).

Optimizing these proteins accelerated recovery of the xanthophyll cycle, which regulates the interconversion between photoprotective zeaxanthin and non-photoprotective violaxanthin under fluctuating light conditions.

By fine-tuning these enzyme levels, the VPZ construct enabled rapid deactivation of heat dissipation and quicker resumption of carbon fixation. Field trials showed 14-20% higher tobacco productivity and over 20% increased soybean seed yield without affecting seed quality.

### Strategy II: Engineering Synthetic Shortcuts (Photorespiratory Bypasses)

To solve the glycolate anomaly, scientists are engineering metabolic shortcuts within the chloroplast. By processing glycolate entirely within the chloroplast stroma, plants save energy and release it directly where RuBisCO needs it.

The RIPE project tested three Alternative Pathways (AP1, AP2, AP3) in tobacco, utilizing genes from *E. coli* and algae combined with RNAi to block the native glycolate transporter, PLGG1. A parallel milestone involved the McG cycle (Malyl-CoA Glycerate cycle). This dual-cycle system converts glycolate directly into acetyl-CoA with zero carbon loss.

**Table 1: Comparing Native vs. Synthetic Pathways**

| Metric | Native Photorespiration | Synthetic Bypass (e.g., AP3) | McG Dual-Cycle (C2 Plants) |
|---|---|---|---|
| Location | 3 Compartments | 1 Compartment (Chloroplast) | 1 Compartment (Chloroplast) |
| Mechanism | Multi-organelle recycling | Chloroplastic oxidation/bypass | Direct conversion to acetyl-CoA |

| Metric | Native Photorespiration | Synthetic Bypass (e.g., AP3) | McG Dual-Cycle (C2 Plants) |
|---|---|---|---|
| Carbon Loss | High (released in mitochondria) | Zero (Internal recycling) | Zero (Carbon conservation) |
| Yield Impact | 20-50% Potential Loss | ~40% Biomass increase (Tobacco) | 2-3x Biomass (*Arabidopsis*) |

**Strategy III: Concentrating Carbon**

Algae and certain hornworts utilize $CO_2$-Concentrating Mechanisms (CCMs) to overcome the catalytic limitations of RuBisCO by concentrating $CO_2$ around the enzyme in the form of $HCO_3^-$ (bicarbonate) within specialized organelles called pyrenoids. Modeling studies suggest that introducing pyrenoid-based CCMs into C3 crops could improve water and nitrogen use efficiency.

Recent studies identified a single-component system, RbcS-STAR, in hornworts that enables spontaneous assembly of RuBisCO into dense compartments without additional linker proteins. Although the organization of these pyrenoid-like structures in higher plants remains incompletely understood, researchers are attempting to engineer $CO_2$ pumps using transporter proteins and carbonic anhydrase enzymes to enhance $CO_2$ concentration around RuBisCO.

Simultaneously, encapsulin-based systems use bacterial protein cages as modular compartments for RuBisCO. By incorporating a 14-amino-acid tag, different RuBisCO isoforms can be efficiently enclosed. Integrating these CCMs into C3 crops such as wheat and rice could increase yields by up to 60%.

**Strategy IV: Rewiring Leaf Architecture (The C4 Rice)**

C4 plants like maize, naturally utilize Kranz anatomy to separate capture from fixation physically. Converting rice, a C3 plant, into a C4 engine requires a total anatomical and biochemical overhaul. Key genetic master switches have been identified to guide this transformation, including *Scarecrow* for bundle sheath patterning and *TOO MANY LATERALS* (*TML*) for vein spacing. The project has achieved three distinct physical prototypes: Biochemical: A functional C4 cycle established within a two-cell radius of existing veins; Chloroplast: Activation of chloroplast development in bundle sheath cells (normally non-photosynthetic in rice), and Structural Anatomy: Increased vein density and altered cell patterning to mimic the Kranz wreath structure.

**Modern Tools:** Beyond traditional transgenics, new precision tools are refining the photosynthetic engine:

- **CRISPR-mediated Regulation:** Rather than inducing gene knockouts, researchers utilize high-throughput simulations of promoter modifications to modulate protein expression. This high-throughput data is used to refine machine learning models of crop genomes.
- **Chemical Agritech:** Sprayable precursors of T6P (Trehalose 6-phosphate) act through the SnRK1 protein kinase pathway to signal sugar abundance. This triggers the plant to divert resources into grain filling, boosting wheat grain size by 20%.
- **QarboGrow Nanotechnology:** Carbon quantum dots are used to convert unusable UV light into photosynthetically active radiation (PAR), effectively widening the spectrum of light available for energy conversion.

**Table 2: Advances and Methods in Photosynthesis Engineering for Crop Improvement**

| Research Strategy | Target Biological Component | Modified Plant Species | Yield Increase Percentage | Environmental Benefit |
|---|---|---|---|---|
| Photorespiratory Bypass (Synthetic glycolate metabolism pathways) | Chloroplast glycolate metabolism and PLGG1 transporter (via RNAi) | Tobacco (*Nicotiana tabacum*) | Up to 40% (biomass) | Prevents energy loss by recycling toxic glycolate entirely within the chloroplast |
| Engineering synthetic Malyl-CoA glycerate (McG) cycle | Carbon fixation cycle (recycled glycolate into acetyl-CoA) | *Arabidopsis* (engineered as C2 plants) | 50% carbon fixation efficiency; 2-3x biomass increase | Significantly higher lipid production for sustainable energy and improved carbon capture |
| Relaxing photoprotection (VPZ construct) | Xanthophyll cycle proteins | Soybean (*Glycine max*) | Over 20% | Greater seed yield without loss of seed quality |
| Chemical T6P precursor spray | Trehalose 6-phosphate (T6P) signalling | Wheat | Up to 20% | Enhanced starch synthesis in grain and improved recovery from drought stress |
| Manipulation of the *Scarecrow* gene | Kranz anatomy (bundle sheath cells and veins) | Maize (*Zea mays*) | Up to 50% (potential) | Genetic key to engineering efficient C4 photosynthesis into C3 crops like rice and wheat |

## Challenges and Translational Constraints

Despite remarkable advances, engineering photosynthesis remains highly complex because photosynthetic pathways are tightly interconnected with plant metabolism, development and environmental signalling. Many engineered traits that perform efficiently under controlled environments may exhibit variable outcomes under field conditions due to temperature fluctuations, light heterogeneity, water limitation, and nutrient availability.

Furthermore, introducing synthetic pathways may impose additional metabolic burden or disrupt native regulatory networks. Regulatory approval, biosafety assessment, public perception of genetically engineered crops, and scalability across diverse agroecosystems also remain major challenges for commercial deployment.

## Conclusion

This overview highlights major bioengineering strategies developed to overcome the inefficiencies of RuBisCO and enhance photosynthetic performance in crops. Approaches such as synthetic photorespiratory bypasses, accelerated photoprotection recovery, $CO_2$-concentrating mechanisms and C4 engineering have shown significant improvements in biomass accumulation, yield and resource-use efficiency. The primary purpose of these innovations is to develop climate-resilient and high-yielding crops capable of sustaining future food demands. With continued advances in synthetic biology, genome editing, and metabolic engineering, these technologies hold great potential for sustainable agriculture and global food security.

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ISSN : 2583-0910
Agri-India TODAY
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Peer reviewed
monthly newsletter

Article ID : 06/VI/63/0626

# ADVANCED SOIL HEALTH MANAGEMENT PRACTICES FOR SUSTAINABLE FARMING

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## Abstract

Sustainable farming is essential for food security, environmental protection, and long-term agricultural productivity. Scientific soil health management improves soil fertility, nutrient availability, and crop productivity through practices such as balanced fertilization, organic manures, crop rotation, conservation tillage, biofertilizers, and precision farming. These approaches enhance water retention, microbial activity, and climate resilience while reducing environmental degradation and excessive chemical use. In India, sustainable soil management also supports efficient resource utilization and improved farmers' income, making it crucial for climate-resilient and sustainable agriculture.

**Key Words:** Soil Health, Sustainable Farming, Soil Fertility, Organic Farming, Precision Agriculture, Biofertilizers, Conservation Tillage, Climate-Resilient Agriculture, Nutrient Management, Sustainable Agriculture.

## Introduction

Soil is the foundation of agricultural productivity, environmental sustainability, and food security. Healthy soil supplies essential nutrients, water, air, and physical support for plant growth while maintaining biological activity and ecological balance. In India, intensive cultivation, excessive chemical fertilizer and pesticide use, soil erosion, declining organic matter, nutrient imbalance, salinity, and water scarcity have seriously degraded soil health and threatened agricultural sustainability. These challenges adversely affect crop productivity, farmers' income, nutritional security, and environmental quality (Padbhushan *et al.*, 2021; Paramesh *et al.*, 2023).

Scientific soil health management practices such as integrated nutrient management, balanced fertilization, conservation tillage, crop rotation, organic amendments, precision agriculture, agroforestry, and efficient water management are helping restore soil fertility and improve resource-use efficiency. Advances in soil testing, digital agriculture, remote sensing, and microbial technologies further support scientific decision-making. Sustainable soil management enhances productivity, conserves natural resources, strengthens climate resilience, and ensures long-term food and environmental security in India. This paper aims to highlight advanced soil health management practices that improve soil fertility, resource-use efficiency, and sustainable agricultural productivity. It also focuses on scientific approaches and modern technologies that support climate-resilient, environmentally sustainable, and economically viable farming systems in India.

## 1. Importance of Soil Health

Indian soils face serious challenges such as nutrient depletion, soil erosion, salinity, declining organic matter, waterlogging, and excessive use of chemical fertilizers. Continuous monocropping and imbalanced nutrient application have reduced soil productivity in many regions. Healthy soils help overcome these problems by improving soil structure, water-holding capacity, nutrient cycling, and beneficial microbial activity, thereby reducing dependence on costly chemical inputs.

Soil health is also vital for climate-resilient agriculture. Soils rich in organic matter store more carbon and moisture, helping crops tolerate droughts, floods, and temperature stress. Practices such as crop rotation, green manuring, conservation tillage, organic farming, integrated nutrient management, and biofertilizer use improve soil fertility and long-term sustainability.

Healthy soils enhance nutrient availability, crop productivity, moisture conservation, carbon sequestration, and environmental protection while reducing erosion and pollution. Government initiatives such as the Soil Health Card Scheme promote balanced nutrient management. Therefore, maintaining soil health is essential for sustainable agriculture, food security, and environmental sustainability in India.

## 2. Recent Advances in Soil Health Management Techniques

Recent advances in soil health management techniques are playing a crucial role in improving agricultural productivity, environmental sustainability, and climate resilience. Modern soil management practices focus on maintaining soil fertility, enhancing soil organic matter, improving microbial activity, and ensuring efficient use of natural resources to ensure agriculture sustainability through climate resilient agriculture. One major advancement is the adoption of precision agriculture technologies such as GPS, GIS, remote sensing, drones, and soil sensors for site-specific nutrient and water management. These technologies help farmers apply fertilizers and irrigation according to crop and soil requirements, reducing input wastage and environmental pollution. Soil testing and digital soil health mapping are also helping in scientific nutrient management.

### Precision Agriculture Technologies:

Precision agriculture technologies are transforming modern agriculture by improving productivity, resource-use efficiency, and environmental sustainability. These technologies use tools such as Global Positioning System (GPS), Geographic Information System (GIS), remote sensing, drones, soil sensors, and Internet of Things (IoT)-based devices to manage crops, nutrients, and water according to site-specific field conditions (Jat *et al*., 2023). Precision farming helps farmers make scientific decisions and optimize agricultural inputs.

GPS and GIS technologies support accurate field mapping, soil sampling, and machinery guidance while analysing variations in soil fertility, crop growth, moisture, and nutrient availability. Remote sensing through satellites and aerial imaging provides real-time information on crop health, soil moisture, nutrient stress, and pest infestation, enabling timely corrective measures.

Drones are increasingly used for crop monitoring, pesticide spraying, nutrient application, and field surveillance. Drone-based spraying reduces labour requirements, saves time, and ensures uniform application of inputs with minimal wastage. Soil sensors and IoT-based devices continuously monitor soil moisture, temperature, salinity, and nutrient levels, enabling precise irrigation and fertilizer application. Automated fertigation and sensor-based irrigation systems further improve water- and nutrient-use efficiency.

Recent advances also include site-specific nutrient management (Dobermann & Cassman, 2022), , customized fertilizers, AI-based advisory services, and mobile decision-support tools. Government initiatives such as the Digital Agriculture Mission, National Mission for Sustainable Agriculture, Pradhan Mantri Krishi Sinchayee Yojana, and Sub-Mission on Agricultural Mechanization promote precision farming technologies in India. These advances improve soil health, conserve water, reduce production costs, and strengthen climate-resilient sustainable agriculture.

**Integrated Nutrient Management (INM):**
Integrated Nutrient Management Systems are increasingly promoted to combine organic manures, biofertilizers, crop residues, and chemical fertilizers for balanced soil fertility. INM improves soil fertility and crop productivity (Paramesh *et al*., 2023; Sande *et al*., 2024). Recent developments in nano fertilizers, customized fertilizers, and microbial biofertilizers have improved nutrient-use efficiency and reduced dependence on excessive chemical inputs. Mentioned below are smart INM techniques.

*Conservation agriculture:* Conservation agriculture practices such as zero tillage, residue retention, cover cropping, mulching, and crop diversification are improving soil structure, moisture conservation, and carbon sequestration. Organic amendments like vermicompost, biochar, and green manures are enhancing soil organic carbon and microbial diversity. Conservation agriculture reduces greenhouse gas emissions and enhances soil organic carbon (Jat *et al*., 2022). These recent advances strengthen sustainable agriculture by improving soil productivity, conserving resources, reducing greenhouse gas emissions, and ensuring long-term food and environmental security.

*Conservation Tillage:* Recent advances in conservation tillage practices are promoting sustainable agriculture and soil health management in India. Conservation tillage involves minimum soil disturbance, permanent soil cover, and crop residue retention to conserve soil and water resources. Modern conservation tillage systems such as zero tillage, reduced tillage, strip tillage, and raised-bed planting are increasingly adopted in major cropping systems, especially the rice–wheat system of North India.

*Zero tillage:* Zero tillage technology has significantly reduced cultivation costs, fuel consumption, and labour requirements while improving soil structure and moisture conservation. The use of advanced machinery such as the Happy Seeder and Super Seeder enables direct sowing of crops into crop residues, reducing stubble burning and environmental pollution.

Recent research highlights the benefits of conservation agriculture in increasing soil organic carbon, enhancing microbial activity, reducing soil erosion, and improving water infiltration. Integration of residue management, cover cropping, and precision nutrient management with conservation tillage further improves nutrient-use efficiency and climate resilience.

Digital technologies, remote sensing, and sensor-based monitoring are also supporting scientific tillage and crop management decisions. Government initiatives promoting climate-smart agriculture and residue management are encouraging farmers to adopt conservation practices. These advances improve soil fertility, conserve water, reduce greenhouse gas emissions, and support sustainable and environmentally friendly agricultural production in India.

The Government of India has launched several schemes to promote conservation agriculture for sustainable soil and water management. The *National Mission for Sustainable Agriculture* encourages practices such as minimum tillage, crop residue management, crop rotation, and integrated farming systems. Under the *Sub-Mission on Agricultural Mechanization*, financial assistance is provided for zero-tillage seed drills, happy seeders, and residue management machinery.

The *Pradhan Mantri Krishi Sinchayee Yojana* supports efficient irrigation and water conservation practices. The *Soil Health Card Scheme* promotes balanced nutrient management and sustainable soil practices. Research organizations such as Indian Council of Agricultural Research and *Krishi Vigyan Kendras* conduct training and demonstrations on conservation agriculture technologies. These initiatives help reduce soil erosion, conserve moisture, improve soil fertility, and promote climate-resilient sustainable agriculture in India.

**Crop Rotation and Diversification**

Crop rotation and diversification are important strategies for improving soil health, farm productivity, and climate resilience in India. Crop rotation involves growing different crops sequentially on the same land, while diversification promotes cultivation of multiple crops and allied enterprises to reduce production risks and increase income. Recent advances include climate-smart crop planning, conservation agriculture, precision farming, and integrated farming systems that support diversified cropping patterns. Digital technologies, remote sensing, and weather-based advisory services help farmers select suitable crop combinations according to soil, climate, and market conditions.

Modern research emphasizes legume-based rotations such as rice–pulse, wheat–mungbean, maize–soybean, and pulse–mustard systems, which enhance soil fertility through biological nitrogen fixation and improve soil organic matter. Diversification towards pulses, oilseeds, millets, vegetables, and horticultural crops reduces dependence on rice–wheat systems and improves nutritional security. These systems also improve water-use efficiency, reduce pest and disease incidence, minimize nutrient depletion, and enhance biodiversity. Integration of fodder crops, medicinal plants, and agroforestry further strengthens sustainable land use. Government initiatives promoting millets, pulses, natural farming, and climate-resilient agriculture are encouraging wider adoption of diversified farming systems across India.

**Intercropping**

Intercropping is a sustainable farming practice in which two or more crops are grown together in the same field. In India, intercropping plays an important role in improving soil fertility, biodiversity, and farm productivity. Legume-based intercropping systems naturally fix atmospheric nitrogen, reducing dependence on chemical fertilizers. Diverse crop root systems improve soil structure, microbial activity, nutrient cycling, and organic matter content.

Intercropping also reduces soil erosion, nutrient leaching, and weed growth by providing better soil cover. Different crops utilize nutrients and moisture from different soil layers, resulting in efficient resource use and balanced nutrient uptake. The practice enhances water-holding capacity and protects soil under adverse climatic conditions. It also supports beneficial insects and soil microorganisms, thereby improving ecological balance. As a result, intercropping strengthens sustainable soil management, climate resilience, and long-term agricultural productivity in India.

**Cover Crops and Mulching**

Cover crops and mulching are increasingly recognized for their role in sustainable soil management and climate-resilient agriculture. Cover crops such as legumes, grasses, pulses, and crop residues protect soil from erosion, improve soil organic matter, enhance microbial activity, and naturally fix atmospheric nitrogen. They also suppress weeds, conserve moisture, and reduce nutrient losses.

Modern mulching technologies, including organic, biodegradable plastic, and residue-based mulches, improve water-use efficiency and regulate soil temperature. Mulching minimizes evaporation, controls weeds, reduces soil compaction, and promotes root growth. These practices also support carbon sequestration and beneficial soil organisms. Integration of cover cropping and mulching with conservation agriculture and precision farming reduces chemical input use, lowers production costs, and improves resilience against drought and climate stress.

**Organic Amendments for Soil Health**

Organic amendments play a major role in restoring soil fertility and improving sustainable agricultural productivity in India. Farmyard manure, compost, vermicompost, green manures, poultry manure, crop residues, and biochar are increasingly integrated into modern farming systems to enhance soil organic carbon and reduce dependence on chemical fertilizers.

Recent advances include enriched composts and fortified organic manures containing beneficial microorganisms and micronutrients. Improved vermicomposting technologies produce nutrient-rich compost with higher microbial activity and better soil-conditioning properties. Biochar is gaining importance due to its ability to improve soil structure, nutrient retention, moisture conservation, and carbon sequestration.

Integration of microbial inoculants, decomposer cultures, and biofertilizers with organic amendments enhances nutrient cycling and soil biological activity. Rapid composting technologies and crop residue management also help recycle agricultural waste efficiently and reduce residue burning. Government initiatives such as the Paramparagat Krishi Vikas Yojana, National Mission for Sustainable Agriculture, and Soil Health Card Scheme promote organic inputs and balanced nutrient management. These practices improve soil fertility, microbial diversity, and climate resilience in Indian agriculture.

**Agroforestry for Sustainable Soil Management**

Agroforestry is significantly contributing to sustainable soil management and climate-resilient agriculture in India. It involves integration of trees, crops, and sometimes livestock on the same land to improve productivity, biodiversity, and environmental sustainability. Scientific agroforestry models combine suitable tree species with crops according to soil type, climate, and farmers’ needs.

Nitrogen-fixing and multipurpose tree species improve soil organic matter, nutrient cycling, and microbial activity. Agroforestry systems reduce soil erosion, improve water infiltration, conserve soil moisture, and enhance carbon sequestration (Kumar *et al*., 2024). Advanced models such as alley cropping, silvopasture, and agri-horticulture are increasingly adopted in different agro-climatic regions of India.

Modern tools such as GIS mapping, remote sensing, and climate-smart planning support scientific management of agroforestry systems. Government programs including the National Agroforestry Policy, Sub-Mission on Agroforestry, National Mission for Sustainable Agriculture, and Green India Mission encourage tree-based farming and sustainable land management. Research institutions and Krishi Vigyan Kendras also provide technical support and farmer training. These initiatives improve soil fertility, conserve moisture, strengthen biodiversity, and support sustainable agricultural development in India.

**Balanced and Efficient Use of Fertilizers**

Excessive dependence on nitrogenous fertilizers, particularly urea, has created serious nutrient imbalances in Indian soils. Continuous and indiscriminate fertilizer use without adequate organic inputs has reduced soil organic carbon, weakened soil structure, and caused deficiencies of secondary and micronutrients. These imbalances adversely affect crop productivity, food quality, and long-term soil health while contributing to groundwater pollution, eutrophication, and greenhouse gas emissions. Therefore, balanced fertilization is essential for sustainable agriculture, environmental protection, and food security in India.

Recent advances such as nano urea, nano DAP, customized fertilizers, and slow-release fertilizers are improving nutrient-use efficiency and reducing nutrient losses. Precision nutrient management technologies including GPS, GIS, remote sensing, drones, soil sensors, and decision-support systems help farmers identify nutrient deficiencies and apply fertilizers according to site-specific crop needs. Soil testing, digital soil health mapping, and AI-based mobile advisory services further support scientific nutrient management.

Government initiatives such as the Soil Health Card Scheme and National Mission for Sustainable Agriculture promote balanced fertilizer use, integrated nutrient management, biofertilizers, and organic manures. Research institutions and Krishi Vigyan Kendras also provide training and demonstrations on scientific nutrient management practices for sustainable and climate-resilient agriculture in India.

**Integrated Nutrient Management (INM)**

Integrated Nutrient Management (INM) is an important approach for sustainable agriculture that combines chemical fertilizers with organic manures, crop residues, biofertilizers, and micronutrients to maintain soil fertility and improve crop productivity. Integration of vermicompost, green manures, farmyard manure, and crop residues with inorganic fertilizers enhances soil organic carbon, soil structure, and microbial activity. Beneficial microorganisms such as *Rhizobium*, *Azotobacter*, *Azospirillum*, phosphate-solubilizing bacteria, and mycorrhiza improve nutrient availability and nutrient-use efficiency (Paramesh *et al*., 2023; Sande *et al*., 2024).

Recent advances in INM focus on precision nutrient management through soil testing, GPS, remote sensing, drones, and sensor-based fertilizer application, which minimize nutrient losses and environmental pollution. Nano fertilizers, particularly nano urea and nano DAP, are improving nutrient absorption and reducing fertilizer wastage. Climate-smart practices such as residue recycling, conservation agriculture, and balanced use of secondary and micronutrients further strengthen INM systems.

Government initiatives including the Soil Health Card Scheme, National Mission for Sustainable Agriculture, and Paramparagat Krishi Vikas Yojana promote balanced fertilization, organic inputs, biofertilizers, and micronutrient use. Research institutions and Krishi Vigyan Kendras also provide training and demonstrations on INM technologies for sustainable and climate-resilient agriculture in India.

**Role of Soil Microorganisms in Soil Health**

Soil microorganisms play a crucial role in maintaining soil fertility, nutrient cycling, and sustainable agricultural productivity in India (Bhardwaj *et al*., 2022). Beneficial microbes such as bacteria, fungi, actinomycetes, algae, and mycorrhiza decompose organic matter, fix atmospheric nitrogen, mobilize nutrients, and improve soil structure. Scientific advances in soil microbiology have promoted the use of microbial biofertilizers containing *Rhizobium*, *Azotobacter*, *Azospirillum*, phosphate-solubilizing, and potassium-mobilizing microorganisms that enhance nutrient availability, stimulate root growth, and reduce dependence on chemical fertilizers.

Modern technologies such as metagenomics and DNA-based soil analysis are improving understanding of microbial diversity and soil biological functions. Mycorrhizal fungi are particularly important for phosphorus uptake, drought tolerance, and disease resistance. Beneficial microorganisms also contribute to carbon sequestration, climate resilience, and long-term soil sustainability.

Integration of microbial technologies with organic farming, integrated nutrient management, and conservation agriculture enhances microbial activity, soil health, and environmental sustainability. Government initiatives such as the National Mission for Sustainable Agriculture, Paramparagat Krishi Vikas Yojana, and Soil Health Card Scheme promote biofertilizers and balanced nutrient management. Research institutions including ICAR and Krishi Vigyan Kendras support farmer training, demonstrations, and research on microbial technologies for sustainable agriculture in India.

### Water Conservation and Efficient Irrigation

Recent advances in water conservation and efficient irrigation are strengthening sustainable agriculture in India under conditions of water scarcity, climate change, and declining groundwater levels. Micro-irrigation systems such as drip and sprinkler irrigation deliver water directly to the root zone, minimizing evaporation and runoff losses. Drip irrigation combined with fertigation improves both water- and nutrient-use efficiency (FAO, 2023). Solar-powered irrigation pumps are also gaining importance as eco-friendly and cost-effective solutions.

Precision irrigation technologies using sensors, drones, remote sensing, and IoT-based systems help monitor soil moisture and crop water requirements in real time, enabling scientific irrigation scheduling and reducing over-irrigation. Water conservation practices such as rainwater harvesting, farm ponds, mulching, conservation agriculture, and watershed management further improve water-use efficiency. Promotion of climate-resilient crops and water-saving practices such as direct-seeded rice also helps reduce water consumption.

Government initiatives including the Pradhan Mantri Krishi Sinchayee Yojana, National Mission for Sustainable Agriculture, Atal Bhujal Yojana, and PM-KUSUM Scheme promote micro-irrigation, groundwater conservation, watershed development, and solar irrigation systems. Research institutions and *Krishi Vigyan Kendras* provide training on scientific irrigation practices. These advances improve crop productivity, conserve natural resources, and support climate-resilient sustainable agriculture in India.

### Integrated Farming Systems

Integrated Farming Systems (IFS) are emerging as an effective approach for sustainable agriculture in India by improving productivity, biodiversity, and soil health (Ravisankar *et al.*, 2023). IFS integrates crops, livestock, fisheries, poultry, agroforestry, mushroom cultivation, vermicomposting, and biogas production to enhance resource-use efficiency and farm income.

Recent advances include precision irrigation, drip systems, solar energy, biofertilizers, protected cultivation, and digital farm management tools. Mobile advisory services and sensor technologies help farmers manage water, nutrients, and livestock efficiently. Crop–livestock–fish systems improve soil fertility, diversify income, and strengthen nutritional security.

Recycling crop residues and animal waste into compost and biogas reduces dependence on chemical fertilizers and external inputs. Climate-smart IFS models also help farmers cope with droughts, floods, and market uncertainties. Continuous recycling of organic materials enhances soil organic carbon, microbial activity, nutrient cycling, and water-holding capacity.

Government programs and research institutions promote region-specific IFS models that conserve resources, improve ecological balance, and support climate-resilient sustainable agriculture in India.

## Soil Amendments for Problem Soils

Recent advances in soil amendments are helping reclaim saline, sodic, acidic, waterlogged, and degraded soils in India through sustainable soil management. Scientific approaches focus on restoring soil fertility, improving soil structure, and enhancing crop productivity. Gypsum is widely used for sodic soils, while lime and dolomite correct soil acidity and improve nutrient availability.

Organic amendments such as biochar, vermicompost, farmyard manure, green manures, and crop residues enhance soil organic carbon, microbial activity, aggregation, and water-holding capacity. Biochar is particularly valuable for nutrient retention, carbon sequestration, and long-term soil health (Agegnehu *et al*., 2021). Biofertilizers and microbial amendments further improve nutrient availability and reduce soil toxicity.

Advanced technologies such as GIS, remote sensing, and soil mapping support site-specific reclamation and nutrient management. Government programs including the Soil Health Card Scheme and National Mission for Sustainable Agriculture promote integrated soil fertility management, organic amendments, and farmer training for sustainable soil health and agricultural productivity in India.

## Precision Agriculture Technologies

Recent advances in precision agriculture are transforming Indian farming by improving productivity, resource-use efficiency, and environmental sustainability. Precision agriculture uses technologies such as GPS, GIS, remote sensing, drones, artificial intelligence (AI), and IoT-based sensors to manage crops, soil, water, and nutrients according to site-specific requirements. These tools help monitor soil moisture, crop health, nutrient status, pests, and weather conditions in real time.

Drone technology is increasingly used for crop surveillance, pesticide spraying, and nutrient application, reducing labour costs and input wastage. Sensor-based irrigation and automated fertigation systems improve water- and fertilizer-use efficiency, while mobile apps and digital advisory platforms provide timely information on weather, disease management, and crop practices. Satellite-based monitoring and variable-rate technologies enable precise nutrient and irrigation management, reducing production costs and environmental pollution.

Government initiatives such as the Digital Agriculture Mission, Pradhan Mantri Krishi Sinchayee Yojana, Sub-Mission on Agricultural Mechanization, and National Mission for Sustainable Agriculture promote precision farming and climate-smart agriculture. Research institutions and Krishi Vigyan Kendras also provide training and technical support. Adoption of these technologies improves soil health, conserves natural resources, enhances climate resilience, and strengthens sustainable agriculture in India.

## Summary and Conclusion

Sustainable soil management is essential for improving soil health, food security, and environmentally sustainable agriculture. Practices such as balanced nutrient management, organic farming, crop rotation, conservation tillage, biofertilizers, residue recycling, and efficient water management enhance soil fertility, microbial activity, and moisture conservation while reducing land degradation and chemical dependence. These approaches improve crop productivity, climate resilience, and long-term sustainability. Strengthening farmer awareness, scientific research, and supportive government policies is crucial for restoring soil health and ensuring sustainable agricultural development in India.

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ISSN : 2583-0910

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Peer reviewed monthly newsletter

Article ID : 06/VI/64/0626

# HOMEMADE PESTICIDES: A WAY TO SUSTAINABLE PEST MANAGEMENT

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## Introduction

Organic gardening has been reported to bring novelty in crop production, enabling manufacturers to meet grower's demand for efficient but natural pest control products. These organic products are no longer exclusive to specialised nurseries or mail order catalogues, instead one can avail them from nearby local stores easily and cheaply. Pests pose a serious threat to plant by restricting their active growth and development. Application of chemical pesticides is not only harmful to environment and natural habitat, but also causes a number of human ailments like respiratory disorders and cardiovascular issues. They are also responsible for degradation of soil health, as they leave their residual toxicity for a considerable period of time. Natural home pesticides are not only convenient to prepare, also they are cheaper and safer than many of the synthesized products available in market.

**Points to be considered before going for application of organic pesticides:**

1. Plants must be well nourished organically with application of fully decomposed compost, as strong plants have the potential to withstand the pest attack. Care should be taken not to over-fertilize the plants as they tend to attract pests with their lush green foliage.
2. Use of companion planting to serve as a natural mean for pest avoidance. Companion planting also helps in improving the environmental condition that attracts beneficial insects to garden.
3. Use of barrier cropping to block pests from infesting the desired crop.
4. The date of planting should be adjusted to avoid the peak insect population period.
5. Use of resistant and tolerant varieties should be encouraged.
6. Addition of beneficial pests to garden can also serve the purpose as they are highly efficient in bringing down the pest population by feeding on them. For e.g. lady bird beetle, parasitic wasp etc.

Below mentioned are some of the organic pest control solutions that can be easily prepared at home and are proved to be quite effective against a wide range of garden pests.

**A. Homemade Insect Soap:** Although different kinds of insect soaps are now available in market for organic gardening purpose, gardeners can also prepare homemade soap spray which can be highly effective against aphids, mites, mealybugs as well as caterpillars. Three drops of mild liquid dishwashing liquid is mixed with one quart of water to which a tablespoon full of edible cooking oil is added that ensures adherence of spray liquid to foliage. The plants are drenched with soap solutions, but care should be taken to avoid spray on flowers or when the prevailing temperature goes over $30^0$C to avoid scorching risk in plants.

**B. Garlic spray:** By nature, garlic is enriched with antifungal, antibacterial as well as antiviral properties, making it a potential pesticide. About five bulbs of garlic are peeled, crushed and mixed in 500 ml of water. The mixture is left overnight as such for allowing the garlic to infuse well in water. A small amount of dish wash is added to the mixture and strained with a fine strainer. The strained liquid is further diluted in a gallon of water and kept in spray bottles. This solution can be sprayed once or twice a week over plants that can effectively bring down many of the insect pests.

**C. Tobacco spray:** The nicotine present in tobacco is proven to be fatal to all categories of insect pests. Cigarette butts are gathered to collect one-fourth of the tobacco leaves. These are soaked overnight in one litre of water and stored properly for subsequent use. Application of this homemade insecticidal spray must be avoided on members of Nightshade family (Solanaceae) viz. Petunia, Datura, Potato, Tomato, Eggplant, and Nicotiana flowers as tobacco is supposed to be a carrier of mosaic virus which is quite detrimental for this family.

**D. Epsom salt:** Epsom salt can be either directly sprinkled around the plants or can be dissolved in water to prepare the spray solution. For making the spray, one cup amount of Epsom salts is dissolved in about 19 litres of water, which is then poured in to sprayer and applied to the pest infested plants. This particular spray solution is quite effective against snails, snugs and beetles. Otherwise, it can be sprinkled directly around the base of the plant once a week, which not only deter harmful pests but also provide magnesium to the soil, thereby increase efficiency of plant nutrient uptake.

**E. Vegetable oil spray:** Soap and oil can together make a highly effective insecticidal spray solution. The spray containing oil helps in coating enclosure and smothering soft-bodied insect viz. mites and aphids. A cup of vegetable oil is mixed with a quarter cup of liquid soap and shaken well. The concentrate thus produced can be stored until further use. While going for spray, one tablespoon full of this concentrated liquid is mixed in four cups of water and the spray can be repeated weekly once for obtaining best results.

**F. Hot pepper bug repellent:** In garden, a row of hot chilli pepper plants can be added in order to harness their bug repelling capacity. A hand full of dried hot peppers is ground to dust; care should be taken to protect skin and eyes during powdering the pepper. The evenly ground chilli can be sprinkled around the garden plants for deterring ants and whiteflies. For ensuring their sticking to plants, half cup of ground peppers is added to a quart of horticultural or edible oil and misted over the tops as well as underside of the foliage.

**G. Citrus spray:** A simple citrus spray solution can efficiently bring down the population of aphids as well as other soft-bodied insects. The rind of a lemon is grated and added to boiling water just removed from the heat. The mixture is allowed to be steeped for overnight, and then strained through a cheese or muslin cloth. The mixture is poured in to a spray bottle and applied on both upper and lower surface of the leaves on infested plants.

**H. Rubbing alcohol bug spray:** Alcohol rubbing helps in quick desiccation of bodies of sucking pests such as aphids, thrips and mealy bugs. A cotton swab soaked in rubbing alcohol is directly applied by dabbing on the pests, taking care to avoid direct contact with plants. A cup of alcohol is mixed with a quart of water to prepare a solution which can be safely applied on plants with waxy leaves. It is a quite efficient method for deterring orchid pests.

**I. Bug juice spray:** As the name indicates, it is a quite fascinating method of pest control by using natural bug spray. For this, sufficient amount of offending pests are gathered, at least to make a teaspoon full and then pulverized with the back of a spoon. The mashed bugs are placed in cheese cloth and soaked in two cups of water for overnight. In order to get best results, the prepared bug juice must be used within three days.

**J. Tomato leaf spray:** Tomato is a member of nightshade family, which leaves are enriched with alkaloids namely tomatine & solanine and can be effectively used as insecticide. For preparing this, two cups of chopped fresh leaves of tomato are soaked overnight in one quart of water. The next day the solution is strained and sprayed over infested plants or plant portions. It not only control aphids and many other chewing insects, but also attracts beneficial insects. Care must be taken to avoid the spray on plants belong to same family like brinjals, potatoes or chillies as it may pose a problem of disease spread.

**K. Neem oil spray:** The oil extracted from neem seeds has the potential to disrupt all stages of insect life cycle i.e. egg, larvae and adult, serving as great resource of pest management for organic gardeners. Neem oil is a very powerful hormone disruptor and act as antifeedant. It is bio-degradable and nontoxic to birds, pets, fishes and other wildlife, but quite potent against a range of common garden insects as well as diseases like powdery mildew and other fungal problems. It can be prepared easily at home or can be procured from nearby garden stores. For using neem seed oil, two teaspoons of neem oil and one teaspoon of mild liquid soap are mixed with one quart of water, shaken well and sprayed on affected plant portions. Preventive sprays of neem oil can be done to avoid infestation at first place.

**L. All-purpose homemade spray:** In order to prepare this homemade natural pest repellent, 2-3 garlic bulbs and a small onion are peeled, chopped and made to puree, to which a teaspoon full of cayenne pepper powder is added. The paste is allowed to steep for a period of one hour and then strained and added with liquid detergent and mixed well. The prepared insecticide is sprayed full length on both the upper and under leaf surface uniformly and the remaining can be stored in refrigerated condition up to one week, if desired.

## Conclusion

The above mentioned organic pest control solutions are not only effective but also quite safer to use than the synthesized ones. They can be easily prepared form the available ingredients and are proven to be less detrimental to the surrounding environment, beneficial insects and natural enemies. Many other plants have been reported to have insecticidal qualities, including hyssop, lettuce leaves, onions, pennyroyal, peppermint, and radish leaves. Apart from that, many natural insect predators viz. Praying Mantis, Ladybugs etc. can also be introduced to the cropped area as a mean of sustainable pest management approach.

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