ONLINE ISSN 2583-4339
www.journalworlds.com

Agri JOURNAL WORLD

Volume 6 Issue 2 April-June 2026 Pages 138

PUBLISHED BY LEAVES AND DEW PUBLICATION

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AGRI JOURNAL WORLD
VOL. 6 ISSUE 2 APRIL- JUNE, 2026

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Agri JOURNAL WORLD

www.journalworlds.com
AGRI JOURNAL WORLD
VOL. 6 ISSUE 2 APRIL- JUNE, 2026

www.journalworlds.com
AGRI JOURNAL WORLD
VOL. 6 ISSUE 2 APRIL-JUNE, 2026

ARTIFICIAL INTELLIGENCE FOR CROP DISEASE PREDICTION

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ABSTRACT

Artificial Intelligence (AI) is transforming modern agriculture by improving crop productivity and disease management. Traditional disease detection methods are often time-consuming and less accurate, leading to yield losses. AI technologies, including Machine Learning (ML), Deep Learning (DL), Convolutional Neural Networks (CNN), and image processing, enable rapid and precise disease detection using leaf images, environmental data, and crop information. These tools support precision agriculture by optimizing pesticide use, enhancing crop monitoring, and improving decision-making. Integrating AI with drones, IoT devices, and mobile applications can further strengthen sustainable agriculture, climate resilience, and global food security..

KEYWORDS: Artificial intelligence, crop disease prediction, deep learning, machine learning, precision agriculture

INTRODUCTION

Agriculture plays a vital role in global food security and economic development. Increasing population growth and climate change have created pressure on agricultural systems to improve crop productivity and quality. Crop diseases significantly affect agricultural yield and can lead to severe economic losses for farmers. Traditional disease detection methods depend on manual observation and expert knowledge, which may be slow and inaccurate.

Artificial Intelligence (AI) has introduced advanced solutions for smart farming and crop disease prediction. AI techniques such as machine learning, deep learning, and image processing help farmers identify plant diseases at early stages using leaf images and environmental data. Smart farming technologies improve crop monitoring, reduce labour requirements, and enhance agricultural productivity. AI-based systems can also assist in disease classification, yield prediction, irrigation management, and pesticide optimization (Akkem et al., 2023).

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AGRI JOURNAL WORLD
VOL. 6 ISSUE 2 APRIL-JUNE, 2026

AI TECHNIQUES USED IN CROP DISEASE PREDICTION

Machine Learning (ML) and Deep Learning (DL) are widely used in agricultural disease prediction systems. Machine learning algorithms such as Support Vector Machine (SVM), Random Forest, and Decision Tree are applied for disease classification and crop monitoring. These algorithms analyse crop features, environmental conditions, and image datasets to identify disease patterns.

Deep Learning techniques, especially Convolutional Neural Networks (CNN), have shown high accuracy in detecting crop diseases from leaf images. CNN models automatically extract image features and classify infected regions with greater efficiency than traditional methods. Researchers have used CNN-based systems for detecting diseases in tomato, rice, banana, and grape crops. Smartphone-assisted disease diagnosis systems also help farmers identify crop diseases in real-time (Chen et al., 2022).

Image processing techniques are commonly integrated with AI systems to improve disease recognition. These methods involve image segmentation, feature extraction, and classification. Advanced technologies such as drones, sensors, and IoT devices further support disease monitoring and precision agriculture.

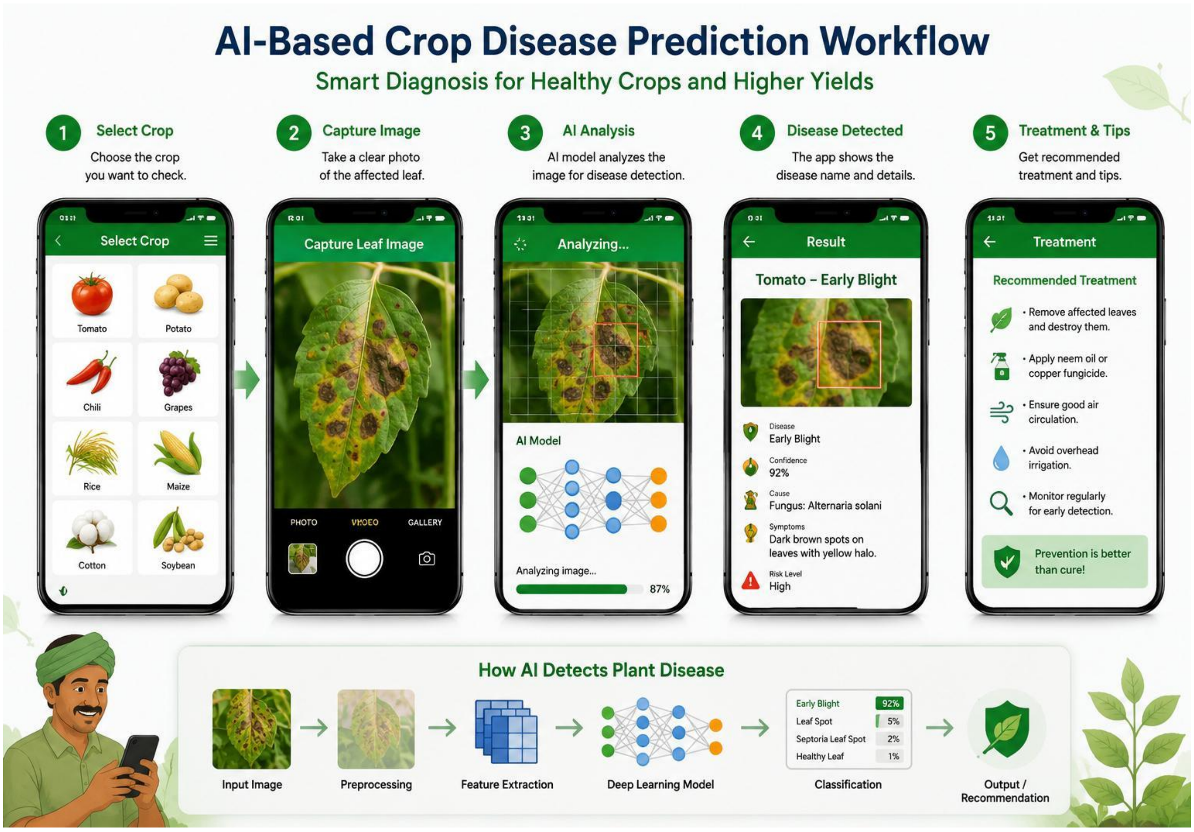

Figure 1. AI-Based Crop Disease Prediction Workflow

APPLICATIONS OF AI IN AGRICULTURE

AI-based crop disease prediction systems are used in various agricultural applications. Disease detection models can identify leaf infections, pest attacks, and nutrient deficiencies with high accuracy. AI technologies support precision farming by reducing excessive pesticide usage and improving crop health management

Machine vision and drone technologies are used for large-scale crop monitoring and disease surveillance. Sensors can collect environmental data such as soil moisture, humidity, and temperature, which are analysed using AI algorithms for predictive farming. AI also assists farmers in irrigation management, yield prediction, and smart greenhouse systems. The use of AI in agriculture improves productivity, reduces labour costs, and supports sustainable farming practices. Smart farming technologies provide efficient decision-making systems that help farmers respond quickly to crop health issues (Kashyap et al., 2024).

CHALLENGES AND FUTURE SCOPE

Although AI provides significant benefits in agriculture, several challenges remain. High implementation costs, limited internet access, and insufficient agricultural datasets restrict the adoption of AI technologies in rural areas. Environmental variations and poor image quality may also affect prediction accuracy.

Future developments in AI-based agriculture are expected to focus on affordable mobile applications, automated drones, and real-time disease monitoring systems. Integration of AI with IoT and cloud computing can improve smart farming efficiency. AI-supported agriculture may play an important role in ensuring food security and climate-resilient farming systems (Sampatirao et al., 2026).

CONCLUSION

Artificial Intelligence has become an important tool for crop disease prediction and smart farming. AI techniques such as Machine Learning, Deep Learning, and CNN provide accurate and efficient disease detection systems. These technologies improve agricultural productivity, reduce crop losses, and support sustainable farming practices. Although challenges such as infrastructure cost and data availability still exist, future AI innovations can transform modern agriculture and strengthen global food security.

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How to cite:

Sundaresh, K. and Balaji, K. (2026). Artificial intelligence for crop disease prediction. Leaves and Dew Publication, New Delhi 110059. *Agri Journal World* 6 (2): 1-4.

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CARBON-NEUTRAL AGRICULTURE AND WEATHER ANALYTICS

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ABSTRACT

Agriculture is a major source of greenhouse gas (GHG) emissions but also offers significant potential for carbon sequestration. Carbon-neutral agriculture aims to balance emissions through mitigation practices and enhanced carbon storage. Advances in weather analytics, climate modeling, remote sensing, and artificial intelligence improve carbon accounting and climate-smart farm management. This review examines emission sources, carbon sequestration mechanisms, weather-based decision support, and Measurement, Reporting, and Verification (MRV) frameworks. Integrating weather analytics with carbon-neutral agricultural practices can improve sustainability, productivity, climate resilience, and contribute to achieving global net-zero emission targets..

KEYWORDS: Carbon-neutral agriculture, carbon sequestration, climate resilience, greenhouse gas emissions, sustainable agriculture, weather analytics

INTRODUCTION

Agriculture is both a major contributor to climate change and one of the sectors most vulnerable to its impacts. Globally, agricultural activities generate substantial emissions of methane (CH_4), nitrous oxide (N_2O), and carbon dioxide (CO_2). At the same time, agricultural lands have the potential to store significant amounts of carbon through improved soil management, agroforestry, conservation agriculture, and biochar application.

Carbon-neutral agriculture aims to achieve a balance between GHG emissions and carbon removals. Advances in weather analytics and climate science provide valuable tools for understanding emission dynamics, predicting climate risks, and supporting adaptive farm management. Integrating weather data with carbon accounting systems enables more accurate assessments of emissions and sequestration potential while improving decision-making for sustainable agricultural production.

CARBON-NEUTRAL AGRICULTURE FRAMEWORK

Carbon-neutral agriculture refers to farming systems where GHG emissions are offset by carbon sequestration or other negative-emission activities. Achieving carbon neutrality requires comprehensive accounting of both emission sources and carbon sinks within agricultural systems.

A robust framework includes:

- Identification of major emission sources.
- Measurement of carbon stocks and sequestration rates.
- Definition of system boundaries.
- Life Cycle Assessment (LCA) methodologies.
- Measurement, Reporting, and Verification (MRV) systems.

Such frameworks support policy development, carbon-credit mechanisms, and sustainable farm management practices.

GREENHOUSE GAS EMISSIONS IN AGRICULTURE

1. *Enteric Fermentation:* Enteric fermentation in ruminants is among the largest agricultural sources of methane emissions. Methane is produced during microbial digestion of carbohydrates in the rumen and released primarily through belching. Globally, enteric fermentation contributes approximately 40–50% of livestock-related agricultural emissions. Improved feed quality, dietary supplements, and efficient production systems can significantly reduce methane intensity.
2. *Manure Management:* Livestock manure generates both methane and nitrous oxide depending on storage and treatment methods. Emissions vary according to animal type, climate, manure handling systems, and storage duration. Improved manure management, anaerobic digestion, and composting can reduce emissions while producing renewable energy.
3. *Rice Cultivation:* Flooded rice fields create anaerobic conditions that promote methane production. Water management practices such as alternate wetting and drying (AWD), improved residue management, and biochar application can substantially reduce methane emissions without compromising productivity.
4. *Soil and Land-Use Change:* Conversion of forests and grasslands to agricultural land often releases large quantities of stored carbon. Conversely, conservation agriculture, reduced tillage, and restoration practices can increase soil carbon storage and reduce emissions associated with land-use change.

5. *Farm Energy and Fertilizer Use:* Farm machinery, irrigation systems, fertilizer manufacturing, and transportation contribute indirectly to agricultural emissions. Nitrogen fertilizers are particularly important because they stimulate N_2O emissions from soils. Precision nutrient management and renewable energy adoption help lower carbon footprints.

CARBON SEQUESTRATION IN AGROECOSYSTEMS

1. *Soil Organic Carbon:* Soil organic carbon (SOC) sequestration is among the most cost-effective climate mitigation strategies available to agriculture. Practices such as conservation tillage, cover cropping, crop rotation, residue retention, and organic amendments enhance soil carbon stocks while improving soil health and water-holding capacity.
2. *Agroforestry and Perennial Systems:* Agroforestry systems integrate trees with crops or livestock, increasing biomass production and long-term carbon storage. Perennial crops and grasses further contribute to carbon accumulation through extensive root systems and reduced soil disturbance.
3. *Biochar and Organic Amendments:* Biochar, produced through biomass pyrolysis, provides long-term carbon storage and improves soil properties. Organic amendments such as farmyard manure, compost, and crop residues enhance soil fertility while contributing to carbon sequestration. Combined organic and inorganic nutrient management often yields the greatest agronomic and environmental benefits.

WEATHER ANALYTICS IN AGRICULTURE

Weather conditions strongly influence crop productivity, carbon cycling, and GHG emissions. Weather analytics utilizes historical observations, real-time monitoring, and predictive models to support agricultural decision-making.

1. Key Meteorological Variables

Important weather variables include:

- Temperature
- Rainfall
- Relative humidity
- Solar radiation
- Wind speed and direction

- Soil moisture
- Drought and flood indicators
- ENSO (El Niño-Southern Oscillation) events

These variables influence crop growth, nutrient cycling, soil respiration, and emission intensities.

2. Climate Variability and Crop Yields

Climate variability significantly affects agricultural productivity. Extreme events such as droughts, floods, heatwaves, and cyclones can reduce yields and increase production risks. Weather analytics helps identify vulnerable regions, improve risk assessment, and support adaptation planning.

3. Predictive Weather Modeling

Weather prediction methods include:

- Statistical models: Regression and time-series techniques.
- Process-based models: Simulation of crop–soil–atmosphere interactions.
- Hybrid and ensemble models: Combining multiple approaches for improved accuracy.

Artificial intelligence and machine learning increasingly enhance forecasting performance, particularly for short- and medium-range predictions.

4. Extreme Weather Risk Assessment

Climate change has increased the frequency and intensity of extreme weather events. Risk assessment tools use historical and forecasted climate data to estimate potential impacts on crop production and carbon budgets. These analyses support insurance products, disaster preparedness, and adaptive management strategies.

INTEGRATION OF WEATHER ANALYTICS WITH CARBON ACCOUNTING

Weather analytics can significantly improve carbon accounting by incorporating climate-driven variability into emission and sequestration estimates.

1. Weather Effects on Emission Intensities: Temperature, rainfall, and soil moisture directly affect methane and nitrous oxide emissions. For example:

- Higher temperatures accelerate organic matter decomposition.

- Excess soil moisture promotes methane production.
- Variable rainfall influences nitrogen transformation processes.

Incorporating weather variables improves emission estimates and reduces uncertainty.

2. *Soil Carbon Dynamics:* Soil carbon sequestration is highly sensitive to temperature and moisture conditions. Weather-driven fluctuations influence soil respiration, organic matter decomposition, and net ecosystem carbon balance. Integrating weather information enhances understanding of seasonal and long-term carbon dynamics.
3. *Seasonal Carbon Budgets:* Carbon budgets vary considerably between seasons due to climate variability. Weather-based assessments help quantify these fluctuations and support adaptive management decisions aimed at maintaining carbon neutrality under changing climatic conditions.
4. *Decision-Support Systems:* Modern decision-support tools integrate weather forecasts, crop models, remote sensing data, and carbon accounting frameworks. These systems assist farmers and policymakers in selecting management practices that maximize productivity while minimizing emissions and climate risks.

MEASUREMENT, REPORTING AND VERIFICATION (MRV)

Reliable MRV systems are essential for implementing carbon-neutral agriculture. MRV frameworks ensure transparent quantification of emissions and removals and support carbon markets, sustainability reporting, and climate policies.

Key MRV components include:

- Standardized methodologies.
- Accurate data collection.
- Monitoring of carbon stocks and emissions.
- Verification procedures.
- Uncertainty assessment.

Advanced technologies such as remote sensing, GIS, IoT sensors, and AI-based analytics can improve monitoring accuracy and reduce reporting costs.

CONCLUSION

Carbon-neutral agriculture represents a promising pathway toward climate-resilient and sustainable food production. Major agricultural emission sources include enteric fermentation, manure management, rice cultivation, fertilizer use, and land-use change, while carbon sequestration can be enhanced through soil management, agroforestry, perennial systems, and biochar application. Weather analytics provides valuable insights into climate variability, emission dynamics, and carbon sequestration processes. Integrating weather forecasting, remote sensing, predictive modeling, and carbon accounting can significantly improve agricultural decision-making and climate mitigation outcomes. Robust MRV systems remain critical for ensuring transparency, credibility, and scalability of carbon-neutral agricultural initiatives. Future research should focus on improving data quality, reducing uncertainties, and developing integrated decision-support platforms that combine carbon accounting with advanced weather analytics.

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How to cite:

Chinchorkar, S. S. (2026). Carbon-neutral agriculture and weather analytics. Leaves and Dew Publication, New Delhi 110059. *Agri Journal World* 6 (2): 5-11.

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NATURE'S BEST FRIENDS: HOW CROPS SUPPORT EACH OTHER IN THE FIELD

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ABSTRACT

Farming is often viewed as a battle against nature, where plants are forced to compete for limited resources. However, agricultural science increasingly shows that crops can also cooperate. This article explores the concept of companion cropping, a practice in which different plants are grown together to support one another. In particular, it examines the practical relationship between Garlic and Coriander, where Coriander helps protect young Garlic plants by moderating sunlight exposure, while Garlic reduces pest pressure through its strong natural odor. By also reviewing classic examples such as maize, beans, and squash, this article demonstrates how working with natural plant interactions can improve crop health while reducing dependence on chemical inputs.

KEYWORDS: Companion cropping, garlic–coriander association, intercropping, pest suppression, sustainable agriculture

INTRODUCTION

Imagine living in a neighborhood where nobody communicates. Every household builds barriers, protects its own resources, and struggles alone. Now imagine a different neighborhood—one where neighbors share tools, look out for each other, and create a safer, more comfortable environment together. This contrast closely reflects the difference between monoculture farming and companion cropping.

For centuries, farmers have observed that certain plants perform better when grown alongside specific companions. Companion cropping is the practice of planting multiple crop species together so that each benefits from the presence of the others. Rather than competing for survival, these plants form natural partnerships. Each crop has its own strengths and weaknesses—some grow tall, some spread wide, some repel pests, and others improve soil health. When these traits are combined intentionally, the field functions as a cooperative system rather than a collection of isolated plants. This article explores such cooperation through the example of Garlic and Coriander, supported by other well-known companion cropping systems.

THE PERFECT PARTNERSHIP: GARLIC AND CORIANDER

A practical and effective example of companion cropping can be found in the pairing of Garlic (*Allium sativum*) and Coriander (*Coriandrum sativum*). While commonly associated with cooking, these two crops demonstrate complementary roles in the field. Their interaction operates through two key mechanisms: microclimate regulation and pest deterrence.

Figure 1. Garlic and coriander grown together in a companion cropping system (Image generated using Google Gemini for illustrative purposes)

1. *Natural Shade for Young Garlic:* Garlic plants are particularly sensitive during their early growth stages. Newly emerged shoots are small and vulnerable to excessive heat and moisture loss. Coriander, on the other hand, establishes rapidly and produces a dense canopy of leaves. When grown together, Coriander partially shades the soil surface, reducing direct exposure to intense sunlight. This moderated environment helps maintain soil moisture and prevents heat stress in young Garlic plants, allowing them to establish more successfully.
2. *Pest Deterrence through Garlic's odour:* Coriander is susceptible to damage from various insect pests that feed on its foliage. Garlic protects its strong aroma, which is produced by sulfur-containing compounds such as allicin. These compounds are widely documented for their insect-repellent properties. When Garlic is grown alongside Coriander, its odour interferes with pest host-finding behaviour, reducing insect infestation without the need for synthetic pesticides. This interaction allows both crops to grow with reduced pest pressure under natural field conditions (Zehnder et al., 2007; Nwauzoma & Dawari, 2013).

Together, these physical and chemical interactions illustrate how companion cropping creates functional relationships that benefit both plant species.

Other Examples of Crop Cooperation

The partnership between Garlic and Coriander is only one of many examples found in traditional and modern agriculture.

THE "THREE SISTERS": MAIZE, BEANS, AND SQUASH

One of the well-documented companions cropping systems is the "Three Sisters," developed by Indigenous farmers of North America. In this system, maize grows vertically and provides structural support for climbing bean plants. Beans contribute to soil fertility by fixing atmospheric nitrogen, making nutrients available to neighbouring crops. Squash spreads along the ground, covering the soil surface with broad leaves that suppress weed growth and reduce evaporation. When cultivated together, these crops create a balanced growing environment that enhances productivity and resource efficiency compared to growing each crop alone.

Figure 2. The traditional three sisters system: Maize, Beans and Squash (Image generated using Google Gemini for illustrative purposes)

1. Tomatoes and Basil: In home gardens and small farms, Basil is frequently planted near Tomatoes. Basil emits aromatic compounds that discourage pests such as tomato hornworms and certain flies. Many growers also report improved plant vigour and flavour quality in Tomatoes grown alongside Basil, making this pairing popular in both culinary and agricultural contexts.

2. Carrots and Onions: Carrots and Onions benefit from each other through mutual pest confusion. Onion odour disrupts the activity of carrot rust flies, while carrot odour interferes with onion flies. By masking each other's presence, these crops experience reduced pest damage without chemical intervention.

WHY THIS MATTERS: IMPLICATIONS FOR SUSTAINABLE AGRICULTURE

Companion cropping has significant implications for the future of agriculture. When crops are selected to complement one another, they form small-scale ecosystems that regulate temperature, moisture, nutrients, and pest populations naturally. Such systems reduce reliance on synthetic fertilisers and chemical pesticides, helping to protect soil health, water quality, and biodiversity.

For a global audience increasingly concerned about sustainable food production, practices like growing Garlic and Coriander together demonstrate that environmentally friendly farming methods are both practical and effective. Rather than forcing crops to survive in isolation, companion cropping encourages cooperation that aligns with natural ecological processes.

CONCLUSION

The idea that crops in a field can be "dost" (friends) is not merely symbolic it reflects real biological interactions that improve agricultural outcomes. The relationship between Garlic and Coriander shows how plants can protect and support one another through shade regulation and pest deterrence. Similar partnerships, such as the Three Sisters system, further illustrate the value of cooperation over competition. By adopting companion cropping techniques, farmers and gardeners move away from intensive control-based practices and toward systems based on mutual support. These examples suggest that the future of agriculture may depend less on chemical inputs and more on understanding and encouraging natural plant relationships.

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How to cite:

Mahato, R., Raj, P. and Ansari, E. (2026). Nature's best friends: How crops support each other in the field. Leaves and Dew Publication, New Delhi 110059. *Agri Journal World* 6 (2): 12-16.

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AGRI JOURNAL WORLD
VOL. 6 ISSUE 2 APRIL-JUNE, 2026

HYPERSPECTRAL IMAGING IN PLANT VIRUS DETECTION: PRINCIPLES, APPLICATIONS, AND FIELD PROSPECTS

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ABSTRACT

Plant viral diseases cause substantial crop losses worldwide and are often detected only after visible symptoms appear. Hyperspectral imaging (HSI) is a non-destructive sensing technology that captures reflected light across hundreds of narrow spectral bands (400–2500 nm), enabling early detection of biochemical changes in infected plants before symptom expression. Integrated with artificial intelligence (AI) and high-throughput phenotyping (HTP), HSI supports large-scale, automated virus detection. This article reviews HSI principles, spectral signatures, sensing platforms, computational analysis, and field challenges, highlighting its potential to advance precision agriculture, disease management, and sustainable food security.

KEYWORDS: Artificial intelligence, high-throughput phenotyping, hyperspectral imaging, plant virus detection, precision agriculture

INTRODUCTION

Plant viral diseases are among the most economically damaging threats in modern agriculture. Infections by Tobacco Mosaic Virus (TMV), Potato Virus Y (PVY), Barley Yellow Dwarf Virus (BYDV), and others reduce photosynthetic capacity and render harvests unmarketable (Bravo et al., 2003). Plant diseases and pests collectively account for 20–40% of global food losses, costing the world economy approximately USD 220 billion annually (John et al., 2023).

Traditional diagnosis relies on visual inspection, enzyme-linked immunosorbent assay (ELISA), or polymerase chain reaction (PCR) methods, which are time-consuming, labour-intensive, and often inaccurate (Behmann et al., 2015). HSI bridges this gap by recording reflectance across 100–500 continuous spectral channels, identifying subtle biochemical changes in plant tissue before visible symptoms manifest (Lowe et al., 2017; Patil et al., 2023). Research has shown that HSI can detect viral infections 5–14 days before visual symptoms emerge, providing a critical early intervention (Kuska et al., 2019).

Principles of Hyperspectral Imaging

A hyperspectral sensor produces a three-dimensional data cube with two spatial dimensions (x, y) and one spectral dimension (λ). At each pixel, a full reflectance spectrum is recorded rather than a single intensity value, encoding surface chemistry, cellular structure, and molecular composition that broad-band systems cannot resolve (Lowe et al., 2017). Three spectral regions carry distinct plant physiological information: (i) the Visible range (VIS; 400–700 nm) governs chlorophyll and carotenoid pigments; (ii) the Near-Infrared (NIR; 700–1000 nm) reflects cell-wall structure and water content, including the diagnostically critical red-edge inflection point at 680–740 nm; and (iii) the Short-Wave Infrared (SWIR; 1000–2500 nm) tracks leaf water status through absorption bands at 970, 1450, and 1940 nm and detects protein and starch disruptions from systemic viruses (Behmann et al., 2015; John et al., 2023). Vegetation indices (VIs) derived from these regions, including Normalised Difference Vegetation Index (NDVI), Green Normalised Difference Vegetation Index (GNDVI), Chlorophyll Index green (CIgreen), and Chlorophyll Index red-edge (CIred-edge), quantitatively assess key parameters such as biomass, chlorophyll content, and canopy structure (Ali et al., 2025).

SPECTRAL SIGNATURES OF VIRUS-INFECTED PLANTS

Viral infection disrupts chloroplast integrity and triggers defensive metabolite accumulation before visible symptoms appear (Kuska et al., 2019). Consistent pre-symptomatic spectral indicators include: (i) reduction in chlorophyll absorption depth at 680 nm (Mahlein, 2016); (ii) blue-shift of the red-edge inflection point from ~725 nm toward 710–715 nm (Yuan et al., 2014); (iii) increased reflectance at 550 nm from carotenoid accumulation and anthocyanin synthesis (Bravo et al., 2003); and (iv) changes in water-band depth at 970 nm and 1450 nm from osmotic imbalance (Lowe et al., 2017) (Fig 1).

Different viruses produce distinguishable spectral profiles. TMV preferentially degrades chlorophyll and creates spatially heterogeneous reflectance maps (Zhao et al., 2022), BYDV triggers systemic yellowing detectable across 500–600 nm (Yuan et al., 2014), and Cucumber Mosaic Virus (CMV) alters canopy-scale backscatter in the SWIR through leaf curl and reduced leaf area (Lowe et al., 2017). Detection accuracy across five major viruses and sensing platforms is summarized in Table 1.

Figure 1: Hyperspectral reflectance spectra of healthy, pre-symptomatic, and virus-infected plants (TMV and BYDV) across 400–2500 nm. Lower panel: difference spectrum (infected − healthy).

Table 1: HSI-based virus detection accuracy across spectral regions

Virus / Disease	Host Crop	Spectral Region	Accuracy (%)
Tobacco Mosaic Virus (TMV)	Tomato, Pepper	400–700 nm (VIS)	91–96
Cucumber Mosaic Virus (CMV)	Cucumber, Squash	700–1000 nm (NIR)	88–93
Barley Yellow Dwarf Virus (BYDV)	Wheat, Barley	1000–2500 nm (SWIR)	87–95
Potato Virus Y (PVY)	Potato	VIS + NIR combined	89–94
Citrus Tristeza Virus (CTV)	Citrus	SWIR + Thermal	85–91

Source: Compiled from Zhao et al. (2022); Yuan et al. (2014); Behmann et al. (2015); Kuska et al. (2019)

COMPUTATIONAL PROCESSING PIPELINE

Raw hyperspectral data requires radiometric calibration, atmospheric correction, and spectral smile correction before analysis (Mahlein, 2016). Dimensionality reduction via Principal Component Analysis (PCA), wavelet transforms, Minimum Noise Fraction (MNF) transformation, or Partial Least Squares (PLS) regression condenses 200–400 spectral bands into manageable components (Patil et al., 2023; Behmann et al., 2015). Machine learning classifiers including support vector machines (SVM) and convolutional neural networks (CNN) then map spectral features to infection status. Integrating automated deep learning CNN algorithms with phytopathology expertise has shown strong promise for accurate disease classification (John et al., 2023; Zhao et al., 2022). (Fig 2) Vegetation indices such as NDVI, Soil Adjusted Vegetation Index (SAVI), and CIred-edge can be computed in real time on embedded hardware for rapid field screening (Ali et al., 2025).

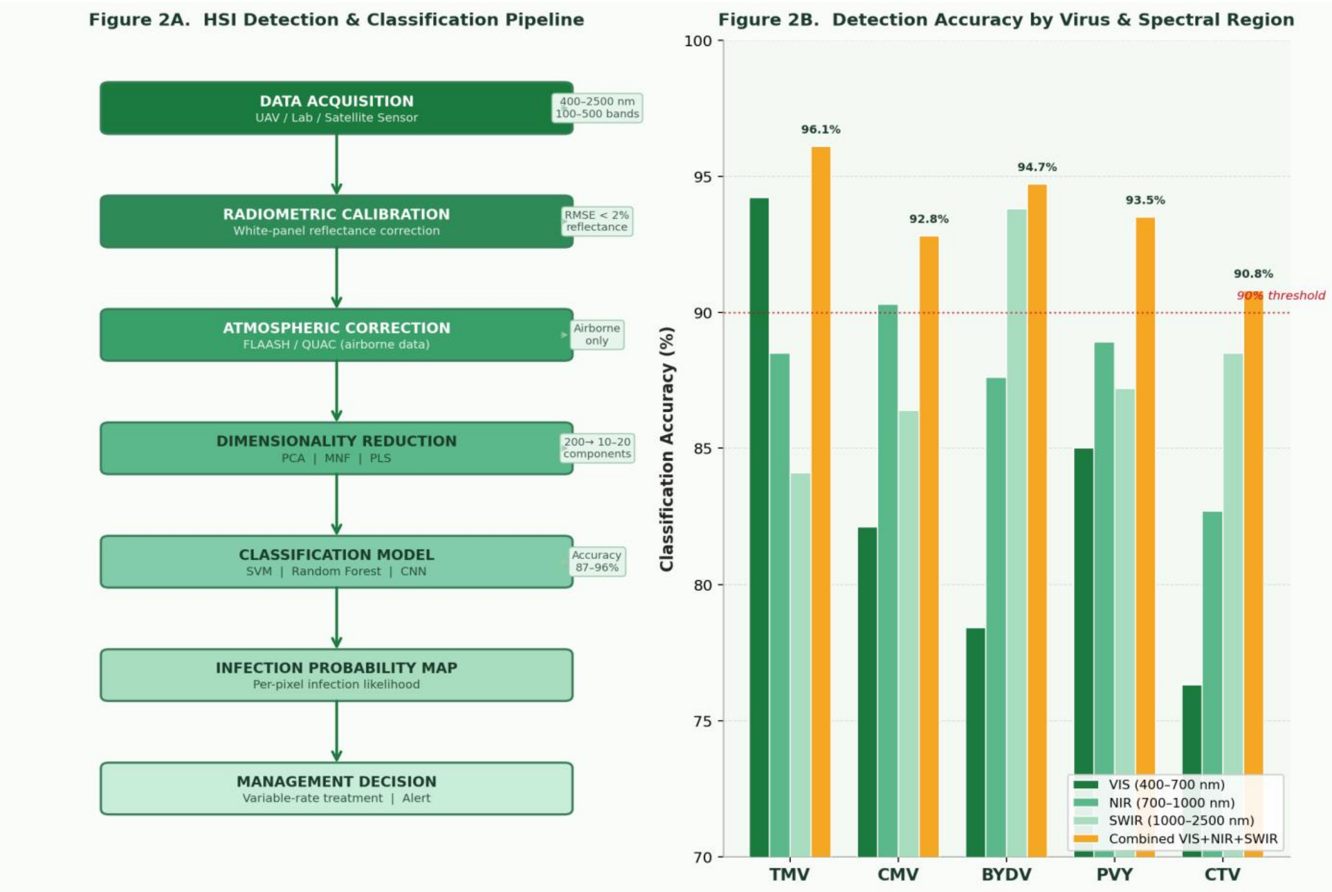

Figure 2: (A) Complete HSI detection and classification pipeline from data acquisition to management decision. (B) Classification accuracy (%) by virus species across VIS, NIR, SWIR, and combined spectral regions; dashed red line = 90% threshold.

SENSING PLATFORMS

HTP platforms employ unmanned aerial vehicles (UAVs) equipped with hyperspectral, multispectral, thermal, and Light Detection and Ranging (LiDAR) sensors (Ali et al., 2025). Laboratory pushbroom line-scan cameras generate labeled datasets for model training (Kuska et al., 2019). UAVs flying at 20–50 m altitude survey several hectares per flight at ground sampling distances of 5–10 cm. Autonomous drones with HSI and AI algorithms efficiently cover large agricultural areas (Patil et al., 2023). Spaceborne sensors such as DESIS (Deutsches Zentrum für Luft- und Raumfahrt Earth Sensing Imaging Spectrometer), PRISMA, and Environmental Mapping and Analysis Program (EnMAP) provide global coverage at 30 m resolution, enabling field-level disease pattern tracking (John et al., 2023).

CHALLENGES AND LIMITATIONS

Viral infection spectral signatures overlap significantly with those from nutrient deficiency, drought, fungal infection, and insect damage, making unique spectral identification of diseases uncertain (John et al., 2023; Behmann et al., 2015). A single hyperspectral flight generates 50–200 GB of raw data, and building well-annotated ground-truth datasets is expensive and labor-intensive (Patil et al., 2023). Model performance degrades when deployed across different growth stages, illumination conditions, or geographic regions (Bravo et al., 2003). High sensor cost and the need for strong digital infrastructure further hinder adoption by smallholder farmers (John et al., 2023).

INTEGRATION WITH PRECISION AGRICULTURE

HSI-derived infection probability maps can trigger variable-rate pesticide applications, flag infected zones for removal, or prompt confirmatory PCR testing within integrated pest management (IPM) frameworks (John et al., 2023; Behmann et al., 2015). The synergy of HTP with VIs accelerates crop improvement by providing precise, high-resolution phenotypic data, supporting the development of resilient, resource-efficient cultivars (Ali et al., 2025). Real-time monitoring systems incorporating HSI sensors provide continuous crop health surveillance (Patil et al., 2023), while standardised data formats such as cloud-optimised GeoTIFF enable interoperability with farm management information systems (FFMIS) (Lowe et al., 2017).

CONCLUSION

HSI has matured from a laboratory tool into a credible field-deployable technology for plant virus detection, capable of identifying infections days before visual symptoms appear (Mahlein, 2016; Kuska et al., 2019). The combination of HSI with AI represents a game-changer for plant disease diagnosis, making detection more rapid, accurate, and affordable (Patil et al., 2023). Integrating HTP platforms with VIs promises to enhance yield prediction, resource management, and sustainable farming practices, ultimately ensuring food security in the face of climate change and global population growth (Ali et al., 2025; John et al., 2023). Addressing remaining challenges in data labelling, model generalizability, and platform cost will require sustained interdisciplinary collaboration across plant pathology, remote sensing, and machine learning.

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AGRI JOURNAL WORLD
VOL. 6 ISSUE 2 APRIL-JUNE, 2026

ARTIFICIAL INTELLIGENCE IN HYDROLOGY: PREDICTIVE MODELLING, PRECISION IRRIGATION, AND AUTONOMOUS NETWORK OPTIMISATION

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ABSTRACT

Rising climate variability and increasing water scarcity demand innovative approaches to water management beyond traditional methods. Artificial intelligence (AI) is transforming modern hydrology by integrating data science with hydraulic engineering to improve water resource management. AI supports predictive modelling of watersheds, precision irrigation in smart agriculture, and intelligent urban water networks. Applications such as satellite-based flood forecasting, machine learning, and automated monitoring systems enable proactive decision-making, reduce water losses, enhance resource-use efficiency, and strengthen resilience against climate-related challenges, ensuring sustainable management of this vital resource.

KEYWORDS: Artificial intelligence, machine learning models, smart agriculture

INTRODUCTION

We are living in an era when data flows as fast as water. For centuries, humanity managed water with a simple, reactive rulebook: when a river floods, build the sandbags higher; when a field dries up, turn on the pump; when a city pipe bursts, send a repair crew to dig up the asphalt. But as climate change alters predictable weather patterns and global populations surge, this old playbook is failing. We are running out of margins for error. To protect our most vital resource, hydrologists are handing over the controls to a new technology: Artificial Intelligence.

By combining classical physics with advanced data science, AI is revolutionising water management, turning it from guesswork into a precise, predictive science. Here's how algorithms are changing our interaction with water, from watershed to kitchen tap.

PREDICTIVE MODELLING: SIMULATING THE WATERSHEDS OF TOMORROW

A watershed is an intricate, dynamic puzzle. Forecasting how a large river basin or a small micro-watershed reacts to a sudden storm involves monitoring hundreds of non-linear factors—such as soil moisture, topography, vegetation cover, evaporation rates, and changing weather patterns. Conventional mathematical models often struggle to analyse this complex web of data in real time.

Hydrologists now utilise advanced neural networks, especially Long Short-Term Memory (LSTM) networks, which are highly effective at analysing sequential, time-series data.

- *Flash Flood Forecasting:* AI analyses real-time data from upstream rainfall gauges, satellite radar, and historical runoff patterns to accurately predict when and where a flash flood will occur, providing crucial early warnings to downstream communities hours in advance.
- *Digital Twins:* AI enables scientists to create a "Digital Twin"—a dynamic, virtual model of a whole river basin. If a policymaker needs to understand how a 15% reduction in seasonal rainfall, paired with quick urban concrete growth, might influence groundwater recharge over the next ten years, the AI can run the simulation in seconds. This facilitates proactive planning that is resilient to climate change.

PRECISION IRRIGATION: THE SMART AGRICULTURE REVOLUTION

Agriculture remains the largest consumer of freshwater, using about 70% of the world’s available liquid. Traditionally, irrigation has involved evenly watering entire fields according to simple schedules, which results in significant water loss through evaporation and runoff.

AI is transforming agriculture through the adoption of Precision Irrigation, which treats fields as a mosaic of moisture zones rather than a single homogeneous block.

- **Predicting Plant Thirst:** Using machine learning models such as Random Forest, AI automatically determines local Evapotranspiration (ET) rates—the precise daily water loss of a crop to the atmosphere. It accomplishes this by combining data from air temperature, solar radiation, humidity, and wind speed.
- **Autonomous Watering:** When integrated with in-field IoT soil moisture probes and real-time weather forecasts, these algorithms manage irrigation automatically. They initiate drip or subsurface watering precisely to meet the plants' water needs. If a rainstorm is forecasted for tomorrow, the

system cancels today's watering schedule. This approach boosts crop yields and reduces water use by up to 30%.

AUTONOMOUS NETWORKS: THE SELF-HEALING CITY

Once water exits a reservoir and flows into a municipal network, it enters a hidden zone. Underground systems often suffer from "Non-Revenue Water"—clean, treated water that is lost through silent, invisible pipe leaks underground before reaching consumers' homes.

AI is turning these dark underground networks into intelligent, autonomous water grids.

- *Acoustic Leak Detection:* When a pipe sustains a microscopic fracture deep underground, the water escaping produces a clear vibrational hiss. Cities are increasingly installing IoT acoustic sensors along their pipelines. AI algorithms analyse this data in real-time, filtering out the loud sounds of city traffic to identify the specific frequency of a leak, and accurately locating its GPS coordinates before a major pipe failure occurs.
- *Dynamic Pressure Management:* Water pressure management requires careful balance. Excessive pressure at night can stress aging pipes and increase leaks. AI studies past usage patterns to forecast daily demand peaks. It then automatically adjusts smart Pressure Reducing Valves (PRVs) to optimise pressure in real-time, creating a self-maintaining system that prolongs pipe life and conserves millions of gallons of water.

CONCLUSION

The integration of Artificial Intelligence, IoT telemetry, and geoinformatics marks a significant shift in how we monitor, model, and protect our planet's water resources. Embedding algorithm-driven systems into watersheds, agricultural areas, and urban infrastructures has evolved hydrology from a purely observational science to a proactive discipline focused on accurate prediction and autonomous management. While obstacles like high setup costs, system compatibility issues, and data security concerns remain, the benefits—such as automated, leak-proof water distribution and adaptive water use in crops based on real-time soil and atmospheric data—highlight the importance of smart networks for climate resilience. Viewing water through a digital lens allows society to manage this scarce resource more efficiently, ensuring long-term availability from large catchment areas to individual users.

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www.journalworlds.com
AGRI JOURNAL WORLD
VOL. 6 ISSUE 2 APRIL-JUNE, 2026

ATMOSPHERIC POLLUTION AND CROP PRODUCTIVITY

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ABSTRACT

Atmospheric pollution is a growing threat to agricultural productivity and global food security. Pollutants such as ozone (O_3), nitrogen oxides (NO_x), sulfur dioxide (SO_2), ammonia (NH_3), volatile organic compounds (VOCs), and particulate matter impair crop growth by reducing photosynthesis, disrupting nutrient uptake, inducing oxidative stress, and lowering yields. Ozone is the most damaging pollutant, especially for cereals. Advances in remote sensing and crop modelling have enhanced monitoring, while sustainable mitigation requires emission control, climate–air quality integration, and pollution-resilient farming practices to protect crop productivity.

KEYWORDS: Air pollution, climate change, crop yield, food security, ozone, particulate matter

INTRODUCTION

Global food demand is expected to increase by 60–110% by 2050 due to population growth and urbanization. Simultaneously, atmospheric pollution continues to intensify, threatening agricultural productivity and food quality. Evidence from many regions indicates that air pollutants significantly reduce crop yields and generate substantial economic losses. Besides affecting plant growth directly, pollution modifies soil properties, climatic conditions, and ecosystem functioning. Understanding pollution impacts on crops is therefore essential for sustainable agricultural development and food security.

MAJOR ATMOSPHERIC POLLUTANTS AFFECTING CROPS

1. *Ozone (O_3):* Ground-level ozone is the most harmful atmospheric pollutant for crops. It enters leaves through stomata and generates reactive oxygen species (ROS), causing oxidative damage to cellular structures. Elevated ozone reduces photosynthesis, accelerates leaf senescence, impairs grain filling, and decreases crop yield. Wheat, rice, soybean, and many horticultural crops are particularly sensitive.

2. *Nitrogen Oxides (NO_x) and Sulfur Dioxide (SO_2):* Nitrogen oxides originate mainly from fossil fuel combustion and fertilizer-related emissions, while sulfur dioxide is released from sulfur-containing fuels. Excess nitrogen deposition may disturb nutrient balance and plant metabolism. Sulfur dioxide contributes to acid deposition and atmospheric haze, negatively influencing crop growth and quality.

3. *Volatile Organic Compounds (VOCs) and Ammonia (NH_3):* VOCs participate in photochemical ozone formation and influence plant physiological processes. Ammonia deposition alters nutrient availability and can suppress photosynthate production. Although their impacts are less studied than ozone, both pollutants significantly affect crop productivity and ecosystem functioning.

4. *Particulate Matter ($PM_{2.5}$ and PM_{10}):*Particulate matter originates from industrial emissions, transportation, biomass burning, and dust storms. Fine particles reduce solar radiation reaching crop canopies, interfere with photosynthesis, and may carry toxic substances. Dust deposition can either supply nutrients or cause toxicity depending on concentration and composition.

MECHANISMS OF POLLUTION-INDUCED YIELD LOSS

1. *Physiological Effects:* Atmospheric pollutants reduce photosynthetic activity, stomatal conductance, transpiration, and nutrient uptake. Ozone-induced oxidative stress damages chloroplasts and decreases carbon assimilation. Root growth and water absorption are also negatively affected.

2. *Biochemical and Molecular Responses:* Pollutants trigger ROS production, antioxidant enzyme activation, and changes in chlorophyll, proteins, and secondary metabolites. These responses often divert energy away from growth and yield formation. Long-term exposure can alter gene expression and increase susceptibility to diseases and environmental stresses.

3. *Indirect Effects Through Soil and Microclimate:* Pollution influences soil microbial communities, nutrient cycling, and mycorrhizal associations. Particulate deposition alters soil chemistry and moisture dynamics, while atmospheric haze modifies temperature and radiation regimes, indirectly affecting crop productivity.

CROP-SPECIFIC RESPONSES

1. *Cereal Crops:* Cereals such as wheat, rice, maize, and barley are among the most pollution-sensitive crops. Ozone exposure reduces grain yield, photosynthesis, and nitrogen-use efficiency. Rice has consistently been identified as one of the most vulnerable cereal species.

2. *Legumes and Oilseeds:* Soybean, common bean, canola, and safflower exhibit moderate sensitivity to atmospheric pollutants. Ozone may reduce seed size, protein content, and overall productivity. Information on many oilseed crops remains limited.
3. *Horticultural Crops:*Fruit trees, vegetables, and ornamental plants frequently exhibit visible injury even under ambient ozone concentrations. Yield reductions may exceed 50% in sensitive species. Pollutants also affect fruit quality, storage life, nutritional value, and marketability.

MONITORING AND MODELING APPROACHES

Ground-based monitoring networks provide valuable long-term observations of pollutant concentrations and crop responses. Remote sensing technologies enable regional assessment of pollution distribution and crop health through indicators such as leaf area index (LAI), gross primary productivity (GPP), and chlorophyll content. Advanced phenomics, hyperspectral sensing, and data assimilation techniques offer new opportunities for monitoring crop stress and improving pollution-impact assessments. Crop models increasingly incorporate pollutant effects to estimate future productivity under changing environmental conditions.

MANAGEMENT AND POLICY STRATEGIES

Mitigating pollution-related crop losses requires both technological and policy interventions. Key strategies include:

- Reducing emissions of ozone precursors and particulate matter.
- Improving fertilizer management to minimize NH_3 and NO_x emissions.
- Developing pollution-tolerant crop varieties.
- Enhancing soil health and nutrient management.
- Expanding air-quality monitoring in agricultural regions.
- Integrating climate-change adaptation with air-pollution control policies.

Climate–air quality co-management offers significant opportunities to protect crop productivity while improving environmental sustainability.

CONCLUSION

Atmospheric pollution is a growing challenge to agricultural productivity and global food security. Ozone, particulate matter, nitrogen oxides, sulfur dioxide, ammonia, and volatile organic compounds adversely affect crop growth through direct physiological damage and indirect changes in soil and environmental conditions. Cereals are particularly vulnerable, while horticultural crops often experience severe quality losses. Advances in monitoring, remote sensing, and modeling have improved understanding of pollution impacts; however, substantial knowledge gaps remain. Sustainable food production under future climatic and environmental conditions will require integrated approaches combining emission reduction, improved crop management, pollution-resistant cultivars, and coordinated climate–air quality policies.

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How to cite:

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www.journalworlds.com
AGRI JOURNAL WORLD
VOL. 6 ISSUE 2 APRIL-JUNE, 2026

CHALLENGES IN GM CROP REGULATION IN INDIA

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ABSTRACT

Genetically modified (GM) crops offer significant potential to enhance agricultural productivity, improve resistance to pests and diseases, and strengthen food security under changing climatic conditions. Although India has strong expertise in plant biotechnology, genomics, and biosafety assessment, commercial adoption of GM crops has progressed gradually. Major challenges include regulatory complexity, public perception, limited commercialization, coordination of field trials, monitoring of unauthorized cultivation, and regulation of imported GM products. Strengthening a transparent, science-based, and efficient regulatory framework will promote responsible innovation while ensuring biosafety and sustainable agricultural development.

KEYWORDS: Agricultural biotechnology, biosafety regulation, food security, regulatory framework

INTRODUCTION

Modern biotechnology has become an integral component of agricultural research worldwide. Genetically modified (GM) crops have been developed to enhance crop productivity, improve resistance to insect pests and diseases, increase tolerance to abiotic stresses, and reduce dependence on chemical pesticides. Since the commercial introduction of GM crops in the mid-1990s, several countries have adopted biotechnology-based crops after comprehensive biosafety evaluations.

India has made significant investments in agricultural biotechnology and has developed substantial expertise in genetic engineering, molecular biology, and crop improvement. The country has established regulatory mechanisms for evaluating the environmental and food safety of GM crops under the Environment (Protection) Act, 1986. While Bt cotton has been successfully cultivated in India since

2002, the commercialization of other GM crops has remained limited. The regulatory framework continues to evolve in response to advances in biotechnology, biosafety requirements, environmental considerations, and public expectations. Understanding the existing regulatory challenges is important for strengthening evidence-based decision-making and promoting responsible use of agricultural biotechnology.

SLOW APPROVAL PROCESS

The regulatory approval process for GM crops in India involves multiple stages of scientific evaluation, including laboratory studies, confined field trials, biosafety assessment, and regulatory review. Such a comprehensive process is essential to ensure environmental and human health safety. However, the duration of regulatory evaluation can sometimes extend over several years, creating uncertainty for research institutions, technology developers, and investors. A more predictable and time-bound regulatory process, while maintaining rigorous scientific standards, could facilitate innovation without compromising biosafety.

PUBLIC PERCEPTION AND AWARENESS

Public perception plays an important role in the acceptance of GM crops. Concerns related to food safety, environmental impacts, biodiversity conservation, and socioeconomic issues have influenced public opinion in India. In many cases, these concerns arise from limited awareness or differing interpretations of scientific evidence. Effective science communication, public engagement, transparent risk assessment, and dissemination of evidence-based information can help improve public understanding and strengthen confidence in regulatory decisions.

LIMITED COMMERCIAL ADOPTION

Although India has demonstrated scientific capability in developing GM technologies for several crops, commercial cultivation has largely been limited to Bt cotton. Consequently, the practical experience with GM technology remains confined to a limited number of traits and crops. Expanding regulatory evaluation of diverse crop traits, wherever supported by scientific evidence and biosafety assessment, would contribute to a broader understanding of biotechnology applications in Indian agriculture while maintaining appropriate regulatory oversight.

COORDINATION IN FIELD TRIALS

Confined field trials are a critical component of the biosafety assessment process because they generate data on agronomic performance, environmental interactions, and potential ecological effects under local conditions. Conducting field trials requires coordination among regulatory authorities, research institutions, state governments, and monitoring agencies. Strengthening institutional coordination and establishing streamlined procedures can facilitate timely generation of high-quality scientific data required for regulatory evaluation.

MONITORING OF UNAUTHORIZED CULTIVATION

Effective monitoring of unauthorized cultivation is important for maintaining the integrity of the regulatory system. Unauthorized use of GM seeds may affect biosafety monitoring, seed quality assurance, and resistance management strategies. Strengthening surveillance systems, improving molecular detection capacity, enhancing seed quality monitoring, and promoting awareness among stakeholders can support effective implementation of existing regulatory provisions and improve traceability of GM planting materials.

IMPORT REGULATION AND GM DETECTION

International trade has increased the movement of agricultural commodities containing genetically modified material. Therefore, robust systems for testing, certification, traceability, and labelling are important for managing imports of food, feed, seed, and research materials. Continued strengthening of laboratory infrastructure, standardized detection protocols, and coordination among regulatory agencies can facilitate effective implementation of import regulations while supporting safe international trade in agricultural products.

FUTURE PERSPECTIVES

Rapid advances in biotechnology, including genome editing and precision breeding, are creating new opportunities for sustainable agricultural development. Regulatory frameworks should continue to evolve alongside scientific progress to ensure that new technologies are assessed using proportionate, science-based, and risk-based approaches. Enhancing transparency, improving stakeholder engagement, strengthening institutional capacity, and promoting international harmonization of biosafety standards can further improve regulatory efficiency while maintaining high standards of safety.

CONCLUSION

India has established a comprehensive regulatory framework for evaluating GM crops with an emphasis on biosafety, environmental protection, and public health. Continued refinement of regulatory processes through greater transparency, scientific rigor, efficient coordination, and evidence-based decision-making will help support responsible innovation in agricultural biotechnology. A predictable, risk-based, and trait-specific regulatory system can facilitate the safe development and evaluation of GM and genome-edited crops while contributing to sustainable agricultural growth, food security, and environmental conservation.

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AGRI JOURNAL WORLD
VOL. 6 ISSUE 2 APRIL-JUNE, 2026

CHAYA BASED PALLETS FEED: WESTE TO WEALTH FOR GOAT

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ABSTRACT

Goat is the backbone of small and marginal farmers in India. India consists of large goat population, but goat farming faces poor nutrition and high disease incidence and seasonal fodder scarcity, which reduces productivity and profitability. Feeding accounts for nearly 70% of the total production cost, making it the most significant economic constraints for farmers. There is a need to adopt cheaper and nutrious feed. In this context, the use of unconventional and locally available fodder like Chaya has gathered attention due to their rich nutritional profile, including high protein content, essential amino acids, minerals, vitamins, and antioxidant properties.

KEYWORDS: Chaya, concentrate, goat, growth, feed, milk, nutrition

INTRODUCTION

Goat farming plays a pivotal role in the livelihood of small and marginal farmers in India, offering a dependable source of income, milk, meat, and manure. Providing the livestock keepers, a cheap source of quality fodder will benefit both the producers as well as consumers. Feed is a crucial component of the ruminant livestock production system, directly influencing growth, productivity, reproduction, and health. The availability of high-quality and sustainable feed remains a significant challenge, particularly in predominantly tropical country like India. The allocation of land for cultivating green fodder crops is limited, accounting for only about 4.9 per cent (9.13 million hectares) of the country's gross cropped area. Moreover, this area has remained stagnant for the last 25–30 years. As a result, the need for alternative feed sources that are cost-effective, easily accessible, highly nutritious, and environmentally sustainable has become a priority. Feeding Chaya (Cnidoscolus aconitifolius) to goats offers benefits like high protein, minerals (Ca, K), and essential amino acids, improving growth, weight gain, and nutrient digestibility, potentially as a partial protein source replacement, while its bioactive compounds may offer antioxidant effects and help balance rumen pH, leading to better feed efficiency and milk and meat quality in goats, but processing (drying/pelleting) might be needed to manage anti-nutritional factors.

Traditionally, shrubs and trees are used as feedstuff to supply livestock with energy, protein, and other nutrients (Papachristou and Papanastasis, 1994). Some of the most common trees and shrubs used in the diets have been shown to improve body growth (Aggarwal et al., 2026) and milk production Totakul et al., 2022). The use of tree leaves in animal feeding has been practiced for a long time. Fodder tree leaves are of particular importance because they contain a high level of CP, therefore, they are typically used for feeding buffaloes, dairy cattle, and goats. However, the potential use of an ingredient is commonly determined not only by its CP content but also by the rumen degradability, palatability, and the associative effects with other feeds in the rations (Smith 1992). Moreover, previous studies reported that feed supplement as a fodder tree mixture could enhance ruminal degradation of nutrients, volatile fatty acids (VFA), and microbial growth in the ruminants (Waghorn 2008).

ORIGIN AND DISTRIBUTION OF CHAYA

The Euphorbeaceae family includes the Chaya (*Cnidoscolus aconitifolius*), which is indigenous to Mesoamerica (Central America). The Indian Grassland and Fodder Research Institute in Jhansi was the site of its introduction in India in 2006. It is also known as "tree spinach" and is prized by the indigenous people of the Yucatan peninsula, parts of Honduras, south-east Mexico, Belize, and the Maya region of Guatemala (Martin and Ruberte, 1978).

Recently Indian families from foreign countries have spread the cultivated Chaya varieties in India. Now it is widely available in Kerala. Kerala Ponics was the first company to provide farmers with authoritative information about these Mexican Chaya leaves. With alternate palmate lobed leaves, the Chaya is a deciduous, evergreen shrub that can withstand drought and reach a height of six meters. Additionally, it resists insects and disease. The succulent leaves are 30 cm in length. The plant has spread all over the world because of its tremendous productivity and simplicity of growing. Chaya may be grown all year round and grows swiftly.

NUTRITIONAL BENEFITS

- *Rich in Protein & Minerals:* Chaya leaves are high in crude protein (around 29%), calcium, and potassium, comparable to soybean meal or alfalfa.
- *Essential Amino Acids:* Contains vital amino acids like lysine, leucine, and phenylalanine.
- *Vitamins:* A good source of essential vitamins, contributing to overall health.

PERFORMANCE & HEALTH BENEFITS FOR GOATS

- *Improved Growth:* Studies show improved body weight gain and growth performance in goats supplemented with Chaya.
- *Enhanced Digestibility:* Increases the digestibility of dry matter, crude protein, and fiber.
- *Better Rumen Function:* Balances rumen pH and promotes propionic acid production, reducing methane.
- *Potential Milk Improvement:* Can enhance milk yield and improve milk composition in dairy goats.
- *Cost-Effective Protein:* Can replace a significant portion (up to 75%) of expensive conventional concentrate feeds, making it a cheaper alternative.
- *Sustainable Fodder:* Its high yield, drought tolerance, and pest resistance make it a valuable, sustainable feed source.

CULTIVATION AND PROPAGATION

Chaya is an easy to grow spinach variety in India. Well-draining soil is suitable for growing tree spinach.

- *Planting Cuttings:* Stem cuttings of 6” to 12” long hardwood cuttings with 2-4 nodes are used as cultivars. Dig a pit of size 50 x 5o x 50 (cm) for planting the rooted stem cutting. Fill the pit with a mixture of soil and compost or green manure. When transplanting the cutting starts (rooted cane), fill the soil firmly around it and mulch well. After allowing the ends to dry for a few days to prevent rotting, plant them upright or at an angle, burying at least 1-2 nodes in the soil.
- *Soil and Climate:* Chaya prefers well-draining soil and can grow in either full sun or partial shade. It requires minimal water once established, but should be irrigated during prolonged dry spells.
- *Spacing:* For commercial fodder production, space cuttings about 1 meter apart, with rows 1 to 2 meters apart.

VARIETIES OF CHAYA

While specific localized Indian cultivars of Chaya do not have prominent registered commercial names, four main varieties of *Cnidoscolus aconitifolius* are used globally and thrive in tropical climates like Haryana and other parts of India.

- *Chaya mansa:* The most common variety used for fodder and edible leaves. It has deeply lobed leaves and is essentially spineless, making harvesting and feeding much easier.
- *Estrella:* Known for broad, deeply lobed leaves. It is a sterile variety that does not produce seeds, so it must be propagated exclusively through stem cuttings.
- *Redonda:* Features more rounded, less deeply lobed leaves. It is known for high leaf biomass production in a short period.
- *Picuda:* Characterized by highly pointed leaf edges. Unlike Chayamansa and Estrella, Picuda produces seeds but can sometimes have mild urticating (stinging) hairs.

HARVESTING FOR FODDER

Pruning: Chaya is a rapid grower. Prune the plant using coppicing or pollarding styles (cutting branches or the main trunk back) to encourage dense, bushy regrowth of young, tender leaves.

Frequency: Plants are robust and can tolerate harvesting up to 60% of their foliage without dying.

YIELD

The plant establishes quickly and responds well to regular pruning. You can perform the first harvest about 90 days after planting, with subsequent cuts every 40 to 50 days. Chaya (*Cnidoscolus aconitifolius*), often called Mayan spinach, is a high-yield, drought-tolerant perennial shrub. On average, Chaya fodder yields an annual fresh biomass of 30 to 60 metric tons per hectare.

FEEDING

Chaya is an incredibly nutritious, protein-rich fodder plant, but its raw leaves and succulent stems contain toxic hydrocyanic glucosides. To feed it safely to goat, you must process it first. Follow these specific preparation methods based on requirement of animal. It can be used in the form of meal or in pellets form.

PREPARATION OF CHAYA MEAL

- *Chaya Leaf Meal (CLM):* Harvest young branches and leaves, chop them into small particles, and sun-dry them for 2 to 3 days. Grind the dried leaves into a powder and mix it into commercial feeds. Chaya meal is high in protein, making it an excellent supplement. However, do not feed it as the sole diet. Start by introducing small amounts (e.g., mixing 4% to 10% into their total daily concentrate mix). Some research indicates that up to 10-20% of their daily diet can safely be composed of Chaya leaf pellets or meal. Mix the meal thoroughly with standard concentrate feed, grain, or molasses to make it highly palatable.

- *Inclusion Rate:* Incorporate the dried Chaya Leaf Meal at about 7.5% to 15% of the total feed mixture (or roughly 150g per kg of feed) to replace more expensive protein sources
- *Preparation of Pellets:* Preparing pellets from Chaya leaf meal involves drying, grinding, and compacting the leaves—usually with binding agents like molasses and cassava starch. This process enhances the shelf life, palatability, and nutrient density of Chaya, which is rich in crude protein, essential amino acids, and minerals.

MIX THE INGREDIENTS

To make firm, nutritious feed pellets, the Chaya meal needs binding agents and other nutrient sources

- *Base Mix:* Combine Chaya meal (approx. 50-90% of the mix) with concentrate mixtures like maize, soya, or wheat bran, dal chunni, salt and mineral mixture.
- *Binders:* Add 5-8% molasses to help bind the leaf meal together under pressure.
- *Moisture:* Add water (about 800 ml per 5 kg of the dry mixture) until the material is slightly damp but not mushy. It should hold its shape when squeezed.

PELLETIZE

- *Machine:* Run the mixed blend through a standard commercial or farm-scale flat-die pellet mill (e.g., 3HP to 100 kg/hr capacity).
- *Action:* The pressure and heat generated by the pelletizer will naturally melt the plant starches and lignin, binding the meal into solid, shiny pellets.

STORAGE

- *Final Drying:* Spread the freshly made, warm pellets out to air-dry and cool completely.
- *Storage:* Store the dried pellets in airtight plastic bins or moisture-proof feed bags to prevent spoilage.

COMPOSITION OF INGREDIENTS FOR PREPARATION OF PELLETS WITH CHAYA LEAVES

- Dry Chaya leaves:4
- Maize:8
- Dal chunni: 35

- Wheat bran: 11
- Mustard Cake: 35
- Molasses:8
- Mineral Mixture:2
- Salt:1
- Total:100

Preparation of Chaya Leaf Meal Pellets for Goats

NUTRITIONAL COMPOSITION OF CHAYA LEAVES PELLETS

- Dry matter: 92.59± 0.60
- Organic matter: 90.35± 0.44
- Crude protein: 19.22± 0.23
- Ether extract: 4.49 ±0.18
- Total ash: 9.65 ±0.12
- Nutrient Detergent Fibre: 30.74 ±0.38
- Acid Detergent Fibre: 19.63 ±0.29
- Hemicellulose: 11.06± 0.28

HANDLING TIPS

- When harvesting, always wear gloves or use plastic bags on your hands to protect your skin from the plant's stinging, irritant hairs.
- Boiling the leaves for 5 to 15 minutes neutralizes the toxins completely and removes the stinging hairs, making them safe for any use.
- Preparing Chaya leaf meal for goats requires careful drying or boiling to remove naturally occurring toxic cyanogenic glycosides. To prepare it safely, harvest the leaves, chop them finely to 2-3 mm, and sun-dry them for 2 to 3 days until brittle. Grind the dried leaves into a meal and mix it in small amounts (up to 10-20%) with their regular feed.

CONCLUSION

Chaya tree is a multipurpose crop foliage boasts a high crude protein content and a favourable amino acid profile, outperforming many conventional leguminous feeds. It is also rich in calcium, potassium, and omega-3 fatty acids. Chaya contains flavonoids and tannins that actively manipulate rumen fermentation.

This helps reduce calculated methane emissions while balancing rumen pH. Replacing up to 25% to 35% of expensive concentrate mixtures with Chaya meal supports growth, milk yield, and meat production while significantly lowering overall feed costs.

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Agri JOURNAL WORLD

www.journalworlds.com
AGRI JOURNAL WORLD
VOL. 6 ISSUE 2 APRIL-JUNE, 2026

AGRIVOLTAICS: WHERE FARMING MEETS SOLAR POWER

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ABSTRACT

Agrivoltaics (Agri-PV or solar sharing) is a dual land-use system that combines crop production with photovoltaic energy generation to optimize land productivity. Since crops utilize only a small fraction of incoming solar radiation, surplus sunlight can be converted into electricity with minimal impact on crop growth. Agrivoltaics enhances water-use efficiency, moderates microclimate, reduces soil erosion, and improves resilience to climate stress while supporting biodiversity and shade-tolerant crops. It also diversifies farm income and promotes rural energy access, offering a sustainable and climate-resilient approach despite challenges such as high installation costs.

KEYWORDS: Agrivoltaics, income diversification, solar energy, sustainability

INTRODUCTION

Agriculture today stands at a crossroads. On one hand, the demand for food is increasing due to rapid population growth; on the other, the availability of arable land is shrinking while climate change continues to threaten crop productivity. At the same time, the global push toward renewable energy has intensified the need for land to install solar power systems. This dual pressure on land resources has led to a fundamental question: Can we produce food and energy on the same land without compromising either?

The answer lies in an innovative approach known as agrivoltaics (AV), a system that integrates agriculture and solar energy generation on the same piece of land. Also referred to as Agri-PV, agro-PV, solar sharing, or agri-solar, agrivoltaics represents a transformative step toward sustainable land-use management.

WHAT IS AGRIVOLTAICS?

Agrivoltaics is a technology and land management strategy that allows simultaneous cultivation of crops (or livestock rearing) and generation of electricity through photovoltaic (PV) panels. Unlike conventional solar farms that occupy agricultural land exclusively, agrivoltaics ensures that farming activities continue alongside energy production. The concept was first introduced in 2004 in Japan by Akira Nagashima under the term “solar sharing.” His design was based on a key physiological principle of plants: crops utilize only about 3-6% of total incident solar radiation for photosynthesis. The remaining sunlight is either reflected, transmitted, or dissipated as heat. Agrivoltaics captures this unused portion of sunlight through solar panels, converting it into electricity while still allowing sufficient light for crop growth. This dual-use approach significantly enhances land-use efficiency, making it possible to generate both food and energy from the same area.

TYPES OF AGRIVOLTAIC SYSTEMS

1. Open Agrivoltaic System

Open systems are the most common form of agrivoltaics. In these systems, solar panels are installed above the crops or between crop rows, allowing sunlight to partially reach the plants. The panels are usually mounted on elevated structures so that farm machinery can operate underneath. These systems are particularly suitable for large scale farming and regions with high solar radiation. They offer flexibility in design and allow farmers to continue traditional agricultural practices with minimal disruption.

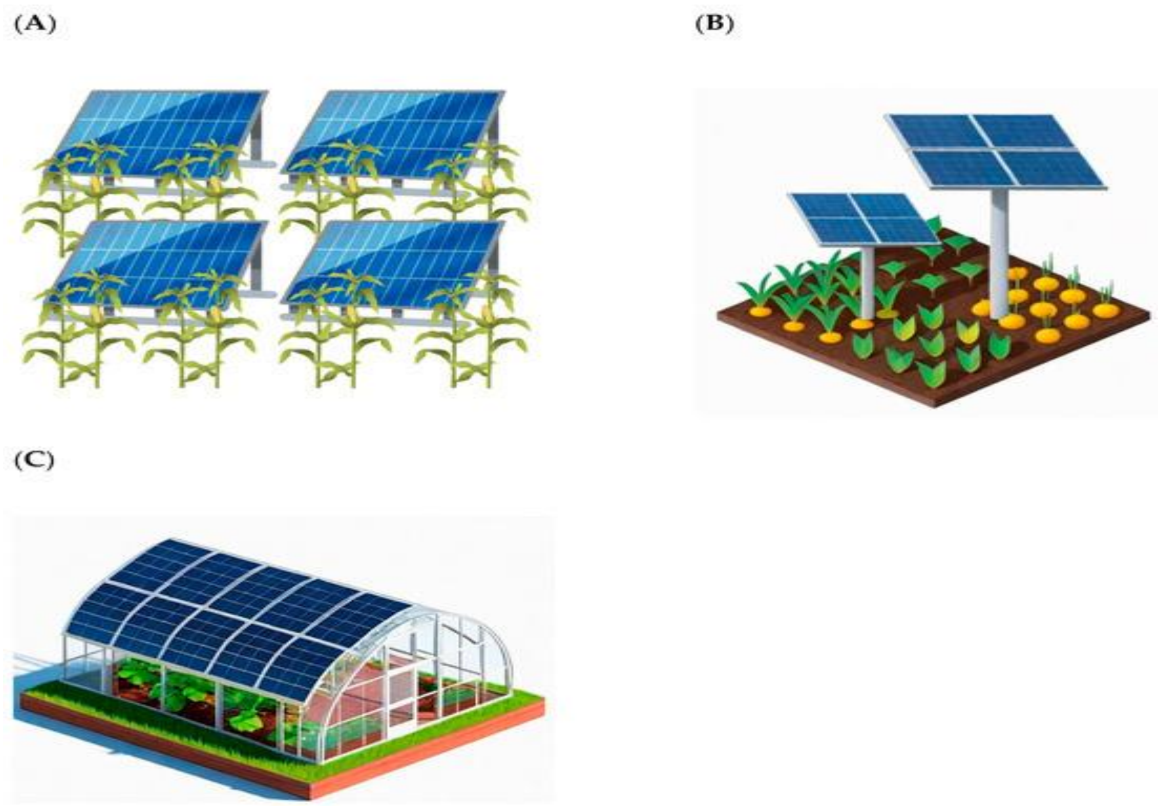

Fig. Different types of agrivoltaic systems. Classified into open systems (A) between crops (B) over crops and (C) closed systems (in a greenhouse structure) (Adopted from Soto-Gómez (2024).

2. *Closed Agrivoltaic System*

Closed systems involve the integration of solar panels into greenhouse structures, either on the roof or walls. These systems require specialized technical design and management. Research indicates that crop production is generally not affected if the panel coverage remains below 20%. However, excessive coverage (50-100%) can significantly reduce light availability, leading to lower crop yields. Interestingly, certain crops such as peppers and leafy vegetables may benefit from partial shading, demonstrating that agrivoltaics can be tailored to specific crop requirements.

ENVIRONMENTAL, ECONOMIC AND SOCIAL ADVANTAGES

A. Environmental Benefits

- One of the most significant advantages of agrivoltaics lies in its ability to enhance environmental sustainability and climate resilience (Kumpanalaisatit et al., 2022).
- Improved Water Use Efficiency: The shading effect of solar panels reduces evaporation from soil and plant surfaces. Studies indicate that agrivoltaic systems can save up to 29% of irrigation water, making them highly valuable in water-scarce regions.
- Microclimate Regulation: Solar panels create a moderated microclimate beneath them by reducing temperature extremes. This helps protect crops from heat stress, which is becoming increasingly common under climate change scenarios.
- Protection from Extreme Weather: Agrivoltaic systems act as a physical barrier against extreme weather events such as hailstorms, heavy rainfall, and intense solar radiation.
- Soil and Biodiversity Enhancement: Reduced exposure to wind and water erosion helps maintain soil health. Additionally, the moderated environment under solar panels can support shade-tolerant crops and promote biodiversity by providing habitats for beneficial insects and pollinators.

B. Economic and Social Benefits

- Beyond environmental benefits, agrivoltaics offers substantial economic and social gains, especially for rural communities.
- Income Diversification: Farmers can generate additional income by selling electricity produced from solar panels. This reduces dependency on a single source of income and enhances financial stability.

- Energy Access and Independence: Agrivoltaic systems can provide clean energy for on-farm operations such as irrigation, storage, and processing. This reduces reliance on fossil fuels and lowers operational costs.
- Enhanced Land Productivity: By combining crop production with energy generation, agrivoltaics increases the overall productivity of land. Instead of choosing between food and energy, both outputs are achieved simultaneously.
- Rural Development: The adoption of agrivoltaics can create employment opportunities, improve infrastructure, and support rural electrification. It also encourages technological advancement in agricultural communities.
- Environmental Sustainability: By replacing fossil fuels with renewable energy, agrivoltaics contributes to reducing greenhouse gas emissions and supports climate change mitigation efforts.

AGRIVOLTAICS IN INDIAN CONTEXT

India, owing to its extensive agricultural sector and abundant solar energy resources, has significant potential for the adoption of agrivoltaic systems. The arid and semi-arid regions of the country, particularly Rajasthan, Gujarat, and Haryana, receive high solar radiation but face challenges such as water scarcity and heat stress, which adversely affect crop growth. In these areas, agrivoltaics offers a promising approach by integrating renewable energy generation with agricultural production (Yadav et al., 2024).

The Government of India aims to achieve 500,000 MW of renewable energy capacity by 2030, including around 300,000 MW from solar photovoltaics. Initiatives like the Kisan Urja Suraksha Evam Utthaan Mahabhiyan (KUSUM) scheme support this target by promoting solar energy use in agriculture and improving farmers' energy security.

CHALLENGES AND TRADE-OFFS

Despite its numerous benefits, agrivoltaics is not without challenges. One of the primary concerns is the balance between crop yield and energy production. Excessive shading can reduce crop growth and yield, whereas insufficient panel coverage may limit energy generation. Therefore, designing agrivoltaic systems requires careful optimization of panel spacing, height, and orientation to ensure that both agriculture and energy production are maintained effectively. Another challenge is the initial investment cost, which can be high for farmers without financial support.

CONCLUSION

Integrating agriculture with photovoltaic technology can simultaneously address the growing requirements of food production and energy generation. India has considerable potential for harnessing renewable energy while ensuring food security for its population. Agrivoltaic systems can contribute to improving farmers' income by enabling dual land use and additional revenue generation. However, supportive policy frameworks and strategic modifications are essential for promoting wider adoption and effective implementation of agrivoltaic systems.

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AGRI JOURNAL WORLD
VOL. 6 ISSUE 2 APRIL-JUNE, 2026

TREE-BASED FARMING SYSTEMS FOR BIODIVERSITY CONSERVATION

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ABSTRACT

Tree-based farming systems, commonly known as agroforestry, integrate trees with crops and livestock to enhance productivity and environmental sustainability. These systems support biodiversity by providing habitats for wildlife, conserving soil organisms, promoting pollinators, and improving ecological connectivity. Unlike monocultures, agroforestry creates diverse ecosystems that enhance carbon sequestration, nutrient cycling, water conservation, and climate regulation. Traditional agroforestry practices have long preserved genetic resources and ecological balance. This article discusses the role of tree-based farming systems in biodiversity conservation, major agroforestry models, their ecological functions, and future prospects for sustainable land management..

KEYWORDS: Agroforestry, biodiversity conservation, ecosystem services, tree-based farming, sustainable agriculture

INTRODUCTION

Biodiversity is essential for maintaining ecological stability and supporting human livelihoods. It includes the diversity of plants, animals, microorganisms and ecosystems that provide valuable services such as pollination, soil fertility, water purification and climate regulation. However, rapid deforestation, urbanization, agricultural intensification and climate change have accelerated biodiversity loss worldwide.

Modern agriculture based on monoculture systems has reduced habitat diversity and ecological resilience. Excessive use of agrochemicals and removal of trees from agricultural landscapes have negatively affected pollinators, birds and soil microorganisms. In this context, tree-based farming systems have emerged as an effective strategy for combining agricultural production with biodiversity conservation.

Agroforestry systems integrate trees with crops and/or livestock on the same land unit. These systems create ecologically diverse landscapes that support wildlife while improving farm productivity and sustainability.

TREE-BASED FARMING SYSTEMS

1. Home Garden Systems

Home gardens are multi-layered farming systems consisting of fruit trees, vegetables, medicinal plants and shrubs around homesteads.

Biodiversity Benefits

- High plant species diversity
- Habitat for birds and pollinators
- Conservation of traditional crop varieties
- Improved soil biodiversity

Home gardens are often called "miniature forests" because of their complex vegetation structure.

2. Agri-Silviculture Systems

Agri-silviculture combines agricultural crops with tree species such as neem, teak, bamboo and poplar.

Ecological Importance

- Improved habitat diversity
- Conservation of beneficial insects
- Reduced soil erosion
- Improved soil fertility and nutrient cycling

Trees improve microclimate and create favourable conditions for biodiversity.

3. Silvo-pastoral Systems

Silvo-pastoral systems integrate trees, pasture and livestock.

Biodiversity Functions

- Conservation of grassland biodiversity
- Wildlife shelter and habitat
- Improved nutrient recycling
- Reduced pressure on natural forests

These systems improve animal welfare while supporting ecological sustainability.

ROLE OF TREE-BASED FARMING SYSTEMS IN BIODIVERSITY CONSERVATION

Habitat Creation

- Trees provide food, nesting sites and shelter for birds, insects, reptiles and mammals. Multi-layered vegetation supports diverse ecological niches.

Pollinator Conservation

- Flowering trees and shrubs provide nectar and pollen resources for bees and butterflies, which are essential for crop pollination.

Soil Biodiversity Enhancement

- Leaf litter and tree roots improve soil organic matter and support microbial communities such as fungi, bacteria and earthworms.

Landscape Connectivity

- Agroforestry systems serve as ecological corridors connecting fragmented habitats and facilitating movement of wildlife species.

Conservation of Native Species

- Traditional agroforestry systems preserve indigenous tree species and local crop varieties adapted to regional climatic conditions.

ECOSYSTEM SERVICES OF AGROFORESTRY SYSTEMS

Tree-based farming systems provide numerous ecosystem services important for environmental sustainability.

Provisioning Services

- Food and fruits
- Timber and fuelwood
- Fodder and medicinal products

Regulating Services

- Climate regulation through carbon sequestration
- Water conservation and groundwater recharge
- Soil erosion control
- Biological pest regulation

Supporting Services

- Nutrient cycling
- Pollination
- Soil formation
- Primary productivity

Cultural Services

- Traditional agroforestry systems preserve indigenous knowledge, cultural heritage and ecological traditions.

TREE-BASED FARMING SYSTEMS AND CLIMATE CHANGE

Climate change threatens biodiversity and agricultural productivity. Agroforestry systems improve resilience against climate variability while contributing to climate mitigation.

1. *Carbon Sequestration*

Trees absorb atmospheric carbon dioxide and store carbon in biomass and soil.

2. *Climate Adaptation*

Agroforestry systems:

- Improve soil moisture retention
- Moderate temperature extremes
- Reduce drought impacts
- Diversify farm income sources

Diverse farming systems are generally more resilient than monoculture agriculture.

CHALLENGES AND FUTURE PROSPECTS

Despite their advantages, adoption of tree-based farming systems faces several constraints.

Major Challenges

- Lack of awareness among farmers
- Policy and regulatory barriers
- Limited quality planting material
- Poor market infrastructure
- Land tenure issues

Future Strategies

- Promotion of native tree species
- Diversified agroforestry models
- Farmer training and extension programs
- Supportive government policies

- Research on biodiversity-friendly agroforestry systems

Community participation and integration of traditional knowledge are essential for successful biodiversity conservation.

CONCLUSION

Tree-based farming systems represent a sustainable approach for integrating agricultural production with biodiversity conservation. By combining trees with crops and livestock, agroforestry systems create ecologically diverse landscapes that support wildlife, improve soil health, conserve pollinators and enhance ecosystem resilience. These systems also contribute to climate change mitigation, restoration of degraded lands and livelihood security. Traditional agroforestry systems demonstrate that conservation and production can coexist harmoniously. Strengthening agroforestry practices through supportive policies, scientific research and farmer awareness can significantly contribute to sustainable development and environmental security.

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DECISION SUPPORT SYSTEMS FOR WEATHER-BASED FARMING

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ABSTRACT

Agriculture is highly vulnerable to weather variability, including droughts, floods, temperature extremes, and pest outbreaks. Weather-based Decision Support Systems (DSS) integrate meteorological data, weather forecasts, crop models, and expert knowledge to provide timely recommendations for irrigation, sowing, harvesting, nutrient management, and pest control. Advances in artificial intelligence, the Internet of Things, remote sensing, and machine learning have enhanced DSS accuracy and predictive capabilities. This review examines their principles, applications, and role in improving climate resilience, resource-use efficiency, risk management, and agricultural productivity under changing climatic conditions..

KEYWORDS: Climate Risk, Crop Modeling, Decision Support System, Irrigation Scheduling, Pest Forecasting, Precision Agriculture, Weather Forecasting

INTRODUCTION

Agricultural productivity is strongly influenced by weather and climate. Variations in rainfall, temperature, humidity, solar radiation, and wind conditions directly affect crop growth, yield, and quality. Extreme weather events such as droughts, floods, heat waves, and storms can cause severe agricultural losses. Consequently, farmers require timely and reliable weather information to make informed management decisions. Decision Support Systems (DSS) have emerged as valuable tools for transforming complex meteorological information into actionable agricultural recommendations. A weather-based DSS combines weather forecasts, agro-meteorological models, crop growth simulations, and expert knowledge to support operational and strategic farm decisions. These systems assist farmers in determining optimal irrigation schedules, planting dates, fertilizer applications, harvesting operations, and disease management strategies.

Modern DSS platforms increasingly integrate artificial intelligence, machine learning, remote sensing, IoT sensors, and mobile communication technologies. Such integration enables real-time monitoring, forecasting, and location-specific advisory services. The effectiveness of a DSS depends largely on the accuracy of weather predictions, availability of local data, robustness of prediction models, and the ability to communicate recommendations in a user-friendly manner. This paper reviews the foundations, architecture, modeling approaches, applications, and evaluation methods associated with weather-based decision support systems in agriculture.

FUNDAMENTALS OF WEATHER-BASED FARMING

Effective agricultural decision-making requires accurate knowledge of future weather conditions. Although weather systems are highly complex, advances in numerical weather prediction now provide reliable forecasts ranging from one day to several weeks. However, many farmers face challenges in interpreting forecast information and applying it to farm operations.

Weather-based DSS bridges this gap by converting meteorological forecasts into practical recommendations. These systems collect, process, analyze, and interpret weather-related information to support crop management decisions. Their primary objective is to minimize production risks while maximizing productivity and resource-use efficiency.

1. *Meteorological Variables and Agro-Climatic Indicators*

- Several weather variables significantly influence agricultural production:
- Rainfall amount and distribution
- Maximum and minimum temperature
- Relative humidity
- Solar radiation
- Wind speed and direction
- Soil moisture status
- Evapotranspiration

These variables affect crop growth, flowering, pollination, grain filling, and maturity. They also influence the development of insects, weeds, and plant pathogens.

Rainfed farming systems are particularly vulnerable to weather variability. In developing countries, a large proportion of farmers depend on rainfall for crop production. Weather-based DSS helps such farmers make timely decisions regarding sowing, irrigation, and crop protection activities based on forecasted weather conditions.

2. Crop Requirements and Phenology

Crop phenology refers to the timing of biological growth stages such as germination, flowering, fruiting, and maturity. Phenological development is largely controlled by environmental factors, especially temperature and moisture.

Weather-based DSS often incorporates phenology models to estimate crop development stages and identify critical periods vulnerable to environmental stress. Phenological information also supports forecasting of pest and disease outbreaks because many pathogens and insects have life cycles closely linked to weather conditions.

Temperature-based growing degree day (GDD) models are widely used to predict crop development and pest emergence. More advanced DSS platforms integrate temperature, rainfall, and soil moisture variables to generate crop-specific recommendations.

ARCHITECTURE OF WEATHER-BASED DECISION SUPPORT SYSTEMS

A typical weather-based DSS consists of three major components:

1. Data acquisition and integration
2. Knowledge representation and inference
3. User interface and visualization

1. Data Acquisition and Integration

The quality of DSS recommendations depends heavily on the quality of data available. Data are obtained from multiple sources, including:

- Automatic weather stations
- Meteorological departments
- Satellite observations
- Remote sensing platforms
- IoT-based field sensors
- Historical climate databases
- Numerical weather prediction models

Data integration allows the system to combine real-time observations with short-term and seasonal weather forecasts. Modern cloud-based architectures facilitate continuous data collection and processing.

Weather forecasts are increasingly coupled with crop simulation models to evaluate potential impacts on crop growth and productivity. Integration of local observations improves forecast accuracy and enables site-specific advisories.

2. *Knowledge Representation and Inference*

Knowledge representation forms the intelligence layer of the DSS. Information may be represented using:

- Rule-based systems
- Expert systems
- Statistical models
- Machine learning algorithms
- Crop growth simulation models

Inference engines analyze relationships among weather variables, crop conditions, soil parameters, and management practices to generate recommendations.

For example, a DSS may combine forecasted rainfall, soil moisture content, and crop growth stage to recommend postponement of irrigation. Similarly, disease warning systems may use temperature and humidity thresholds to estimate disease risk levels.

3. *User Interface and Visualization*

The user interface converts complex analytical outputs into understandable information for farmers and agricultural advisors.

Important visualization features include:

- Weather dashboards
- Interactive maps
- Risk indicators
- Disease warning alerts
- Irrigation advisories

- Mobile notifications

Graphical displays simplify interpretation and facilitate rapid decision-making. Mobile applications have become particularly important because they enable real-time dissemination of weather-based advisories to farmers.

4. Interoperability and Standards

Agricultural DSS often integrate multiple software platforms and databases. Standardized protocols facilitate interoperability among weather services, crop models, remote sensing systems, and farm management platforms.

Web services and open-data standards enhance information sharing across institutions and regions. Such interoperability improves scalability and supports the development of comprehensive climate-smart agricultural advisory systems.

MODELING APPROACHES FOR WEATHER-BASED DECISIONS

Predictive models form the analytical foundation of weather-based DSS. These models transform weather information into forecasts of agricultural outcomes.

1. Predictive Weather Modeling

Weather prediction models estimate future atmospheric conditions using mathematical representations of atmospheric physics.

Forecast horizons generally include:

- Short-term forecasts (1–7 days)
- Medium-range forecasts (7–20 days)
- Seasonal forecasts (1–6 months)
- Climate projections (years to decades)

The India Meteorological Department (IMD) provides operational agricultural weather forecasts that support farm-level decision-making. Modern DSS platforms integrate these forecasts with crop-specific decision rules.

Artificial intelligence and machine learning techniques are increasingly being used to improve forecast accuracy through pattern recognition and adaptive learning.

2. Climate Risk Assessment

Climate risk assessment evaluates the probability and impact of adverse weather events on agricultural production.

Major climate risks include:

- Drought
- Flooding
- Heat stress
- Cold stress
- Salinity
- Extreme rainfall events

Historical climate datasets are analyzed to identify trends and estimate future risks under various climate scenarios. Risk maps generated through GIS and remote sensing technologies assist policymakers, insurance agencies, and farmers in climate adaptation planning.

Sensitivity analyses are frequently conducted to determine crop vulnerability under different climate scenarios such as Representative Concentration Pathways (RCPs).

3. Yield Forecasting and Phenology Modeling

Crop growth and yield forecasting models estimate production outcomes based on weather, soil, and management conditions.

Common modeling approaches include:

- Process-based crop simulation models
- Statistical regression models
- Machine learning models
- Phenological development models

These models predict flowering dates, maturity periods, biomass accumulation, and grain yield. Regional-scale forecasting supports food security planning, drought monitoring, and market intelligence.

Temperature-based thermal indices and growing degree day approaches are widely used for forecasting phenological stages of crops such as wheat, rice, mustard, and chickpea.

4. Pest and Disease Forecasting

Weather conditions strongly influence pest populations and disease development. Consequently, weather-based forecasting systems are important tools for integrated pest management.

Two major approaches are employed:

Mechanistic models: These models simulate biological processes using known relationships between weather variables and pathogen development.

Statistical models: These models use historical weather and pest occurrence data to identify predictive relationships.

Risk forecasting enables farmers to optimize pesticide applications, reduce costs, and minimize environmental impacts. Weather-based disease warnings are particularly useful for crops susceptible to fungal diseases under humid conditions.

DECISION SUPPORT FOR FARM MANAGEMENT

The practical value of weather-based DSS lies in its ability to support farm-level decisions.

1. Irrigation Scheduling

Water management is one of the most important applications of weather-based DSS.

Irrigation recommendations are generated using:

- Weather forecasts
- Evapotranspiration estimates
- Soil moisture measurements
- Crop water requirements

When rainfall is forecasted, irrigation can be postponed, thereby reducing water use and energy costs. Smart irrigation systems increasingly integrate weather forecasts with IoT-based soil moisture sensors for automated decision-making.

2. Planting and Harvest Management

Weather forecasts assist farmers in selecting suitable planting windows and harvest periods.

Benefits include:

- Improved crop establishment
- Reduced seedling mortality

- Avoidance of rainfall during harvest
- Better grain quality

Temperature accumulation models help estimate crop maturity dates and schedule harvesting operations. Seasonal forecasts can also support strategic crop selection decisions.

3. Fertilization and Nutrient Management

Nutrient-use efficiency is highly influenced by weather conditions.

Weather-based DSS supports nutrient management by:

- Predicting nutrient losses due to rainfall
- Estimating crop nutrient demand
- Optimizing fertilizer application timing
- Reducing environmental pollution

Integrated systems combine weather forecasts with crop growth models to generate precise fertilizer recommendations.

4. Disease and Pest Risk Mitigation

Disease and pest outbreaks frequently occur under favorable weather conditions. DSS platforms provide early warning systems that help farmers implement preventive measures.

Typical advisory outputs include:

- Disease risk levels
- Spray timing recommendations
- Pest monitoring alerts
- Integrated pest management strategies

Such systems reduce crop losses while minimizing unnecessary pesticide applications.

EVALUATION, VALIDATION, AND UNCERTAINTY MANAGEMENT

Reliable DSS performance requires rigorous validation and uncertainty assessment.

1. Validation Methodologies

Different components of DSS require different validation approaches.

Examples include:

- Comparing forecasted and observed weather variables
- Validating crop phenology predictions against field observations
- Comparing predicted and actual yields
- Assessing disease forecasts using field surveillance data

Independent validation datasets improve model credibility and operational reliability.

2. Uncertainty Quantification

Uncertainty arises from:

- Weather forecast errors
- Incomplete data
- Model assumptions
- Biological variability
- Climate unpredictability

Quantifying uncertainty enables users to understand the confidence associated with recommendations. Ensemble forecasting methods are increasingly used to estimate prediction uncertainty.

3. Performance Metrics

Common DSS performance indicators include:

- Prediction accuracy
- Root Mean Square Error (RMSE)
- Mean Absolute Error (MAE)
- Probability of Detection (POD)
- False Alarm Ratio (FAR)
- Sensitivity and specificity
- Lead time effectiveness

Evaluation metrics should reflect both technical accuracy and practical utility for farmers.

FUTURE PERSPECTIVES

Emerging technologies are transforming weather-based agricultural decision support systems. Artificial intelligence, deep learning, edge computing, IoT networks, and remote sensing are improving the precision and scalability of agricultural advisories.

Future DSS platforms are expected to incorporate:

- Hyper-local weather forecasting
- AI-powered recommendation engines
- Voice-enabled advisory systems
- Autonomous sensing networks
- Climate adaptation analytics
- Digital twin farming environments

Integration of weather analytics with precision agriculture technologies will further enhance productivity, sustainability, and resilience under changing climate conditions.

CONCLUSION

Weather-based Decision Support Systems represent a critical technological advancement for climate-smart agriculture. By integrating meteorological forecasts, crop growth models, climate risk assessments, and expert knowledge, these systems enable farmers to make informed decisions regarding irrigation, planting, fertilization, harvesting, and crop protection. The incorporation of AI, IoT, remote sensing, and machine learning has significantly improved predictive capabilities and operational effectiveness. Despite challenges related to uncertainty and data availability, continued advances in forecasting technologies and digital agriculture are expected to strengthen the role of DSS in sustainable agricultural development. Widespread adoption of weather-based DSS can improve resource-use efficiency, reduce production risks, enhance climate resilience, and support long-term food security.

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How to cite:

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Agri JOURNAL WORLD
www.journalworlds.com
AGRI JOURNAL WORLD
VOL. 6 ISSUE 2 APRIL-JUNE, 2026

INDIA'S POULTRY REVOLUTION: GROWTH, OPPORTUNITIES, AND ECONOMIC IMPACT

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ABSTRACT

The poultry sector is one of the fastest-growing segments of Indian agriculture, contributing significantly to GDP, employment, food and nutritional security, rural development, and export earnings. India ranks among the world's leading producers of eggs and poultry meat, supported by advances in breeding, feed, biosecurity, automation, and processing. Poultry farming provides affordable, high-quality protein and supports millions of livelihoods across allied industries. Despite challenges such as disease outbreaks, feed costs, and market fluctuations, continued policy support, infrastructure development, and sustainable production practices will strengthen the sector's long-term growth and global competitiveness.

KEYWORDS: Employment generation, nutritional security, poultry exports, poultry farming, poultry sector, rural development

ROLE OF POULTRY SECTOR IN THE GROWTH OF INDIA'S ECONOMY

The poultry sector is one of the fastest-growing and most organized segments of Indian agriculture. Over the years, poultry farming in India has evolved from traditional backyard systems into a highly commercialized, technology-driven, and integrated industry. This transformation has significantly enhanced the contribution of the poultry industry to economic growth, employment generation, food security, and rural development. The poultry sector has become a crucial component of the Indian livestock economy and plays a strategic role in improving the socio-economic conditions of millions of people. According to the 20th Livestock Census, India's poultry population reached 851.81 million birds in 2019, including 317.07 million backyard poultry and 534.74 million commercial poultry birds, representing a growth of 16.81% over the previous census (DAHD, 2019). This rapid increase demonstrates the expanding scale and commercialization of the sector. India currently ranks second globally in egg production and among the top poultry meat-producing countries in the world (FAO, 2023). The poultry industry has emerged as a major driver of economic development due to its extensive backward and forward linkages with agriculture, feed manufacturing, veterinary healthcare, food processing, transportation, and retail marketing sectors. Poultry farming contributes significantly to the livelihoods of rural households, particularly small and marginal farmers, landless labourers, and women entrepreneurs.

ECONOMIC CONTRIBUTION AND INDUSTRIAL GROWTH

The poultry industry contributes substantially to India's agricultural GDP and national economy. The sector includes broiler production, layer farming, hatcheries, feed manufacturing, poultry equipment industries, vaccine production, processing plants, and export-oriented enterprises. India's poultry sector contributes more than ₹1,20,000 crores annually to the national economy and supports millions of direct and indirect jobs (BAHS, 2024). India has witnessed remarkable growth in both poultry meat and egg production. According to BAHS (2024), total meat production in India reached 10.25 million tonnes during 2023-24, of which poultry contributed nearly 48.96%. Poultry meat production has increased steadily due to rising consumer preference for affordable white meat. Simultaneously, India's egg production reached 142.77 billion eggs during 2023–24, reflecting consistent annual growth. Commercial poultry systems dominate egg production, although backyard poultry still contributes significantly to rural nutrition and livelihood security. The per capita availability of eggs increased from 62 eggs per year in 2014-15 to 103 eggs per year in 2023-24 (DAHD, 2024). This increase highlights the growing accessibility of affordable animal protein among the Indian population. The poultry industry has strong multiplier effects across several allied industries. Feed manufacturing alone constitutes one of the largest associated sectors, utilizing large quantities of maize and soybean meal. The growth of poultry farming has therefore created stable markets for crop farmers and stimulated agricultural commercialization.

EMPLOYMENT GENERATION AND RURAL LIVELIHOOD SECURITY

One of the most significant contributions of the poultry sector is large-scale employment generation. Poultry farming creates direct employment opportunities in farms, hatcheries, feed mills, slaughterhouses, and processing industries. It also generates indirect employment in transportation, veterinary services, packaging, equipment manufacturing, cold chain logistics, and retail marketing. Industry estimates indicate that the poultry sector supports nearly 6 million farmers, workers, and entrepreneurs across India (DAHD, 2024). The decentralized nature of poultry farming makes it particularly beneficial for rural development. Small-scale poultry enterprises require relatively low initial investment and provide quick returns due to the short production cycle. Poultry farming has become an important source of supplementary income for small and marginal farmers. Unlike seasonal crop farming, poultry production generates continuous cash flow throughout the year, thereby reducing financial vulnerability and stabilizing rural household income. Women empowerment is another major advantage associated with poultry farming. Backyard poultry rearing is predominantly managed by women in rural and tribal areas.

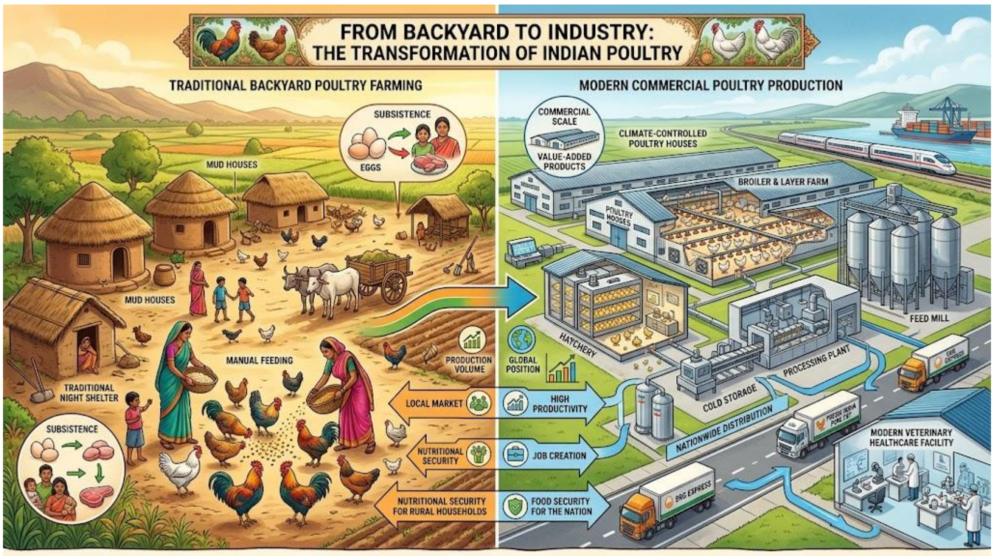

Figure 1. Growth and modernization of the Indian poultry sector: Transition of Indian poultry farming from backyard systems to modern commercial poultry production integrating automated feeding systems, climate-controlled housing, hatcheries, feed mills, processing units, and cold chain logistics.

Income generated from poultry farming enhances women's financial independence and decision-making capacity within households (Thirunavukkarasu and Geetha, 2018) Government-supported self-help groups and poultry development programs have further promoted women entrepreneurship in the sector. The poultry sector also encourages youth entrepreneurship. Many educated rural youth are adopting commercial poultry farming as an agribusiness venture due to increasing market demand and profitability (Singh and Kumar, 2021). Thus, the poultry industry contributes significantly to reducing rural unemployment and migration.

NUTRITIONAL SECURITY AND PUBLIC HEALTH IMPORTANCE

The poultry sector plays a critical role in improving food and nutritional security in India. Protein-energy malnutrition and micronutrient deficiencies remain major public health concerns, especially among children, pregnant women, and economically weaker populations. Eggs and chicken meat are considered among the most affordable and accessible sources of high-quality animal protein. Eggs contain balanced amino acids, vitamins, and minerals including vitamin A, vitamin B12, folic acid, riboflavin, selenium, iron, and phosphorus. Due to their superior biological value, eggs are often referred to as a complete food. Chicken meat is also an excellent source of protein with comparatively lower fat content than many other meats. Increased consumption of poultry products contributes significantly to improved dietary diversity and nutritional adequacy. Several government nutrition programs, including school mid-day meal schemes and Integrated Child Development Services (ICDS), have incorporated eggs into feeding programs because of their affordability and nutritional benefits. Increased egg consumption has been associated with improved growth, cognitive development, and health outcomes among children. Backyard poultry farming also improves household nutritional security by ensuring direct access to eggs and meat in rural and tribal communities. Therefore, the poultry sector contributes not only to economic growth but also to improved public health and human capital development.

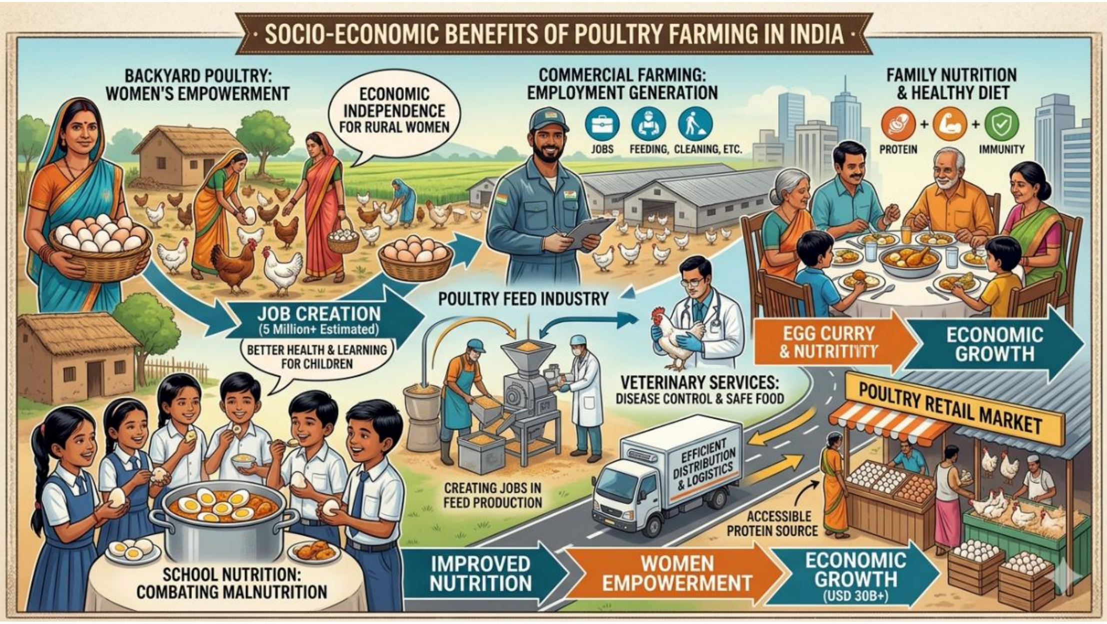

Figure 2. Poultry sector contribution to employment and nutritional security: The socio-economic benefits of poultry farming including employment generation, women empowerment, rural livelihood improvement, affordable protein supply, and enhanced nutritional security among Indian households.

TECHNOLOGICAL ADVANCEMENT AND MODERNIZATION

The rapid expansion of the poultry industry has accelerated technological advancement within Indian agriculture. Modern poultry farming increasingly incorporates scientific management practices, automation, biotechnology, precision nutrition, and disease surveillance systems (Chatterjee and Rajkumar, 2015). Genetic improvement programs have produced high-yielding broiler and layer strains with superior growth performance and feed conversion efficiency. Commercial broilers can now attain market weight within 35-42 days, while modern layer birds can produce more than 300 eggs annually under optimal management conditions. Feed technology has also advanced considerably. Scientific feed

formulation, enzyme supplementation, probiotics, toxin binders, and precision nutrition strategies have improved feed efficiency and bird performance. These developments have strengthened the feed manufacturing industry and increased demand for agricultural commodities such as maize and soybean. Automation and mechanization have become increasingly common in commercial poultry operations. Environmentally controlled poultry houses equipped with automated feeders, nipple drinkers, ventilation systems, and egg collection systems have improved productivity and reduced labour requirements. Biosecurity and disease prevention have become central to modern poultry management. Vaccination programs, molecular diagnostics, and disease surveillance systems have significantly reduced production losses caused by infectious diseases. The veterinary pharmaceutical and vaccine industries have therefore expanded substantially alongside poultry sector growth. The poultry industry has additionally stimulated investment in cold chain infrastructure and food processing industries. Modern slaughterhouses, refrigerated transport systems, and processing plants have improved food safety standards and shelf life of poultry products.

CONTRIBUTION TO AGRICULTURE AND ALLIED INDUSTRIES

The poultry sector maintains strong interconnections with multiple agricultural and industrial sectors. Poultry feed manufacturing creates substantial demand for maize and soybean meal, thereby supporting crop farmers and agricultural markets. India's expanding poultry industry has significantly increased maize consumption, creating stable market opportunities for maize growers. Similarly, soybean cultivation has benefited from increasing demand for soybean meal used in poultry feed. The veterinary pharmaceutical industry has also grown rapidly due to rising demand for vaccines, antibiotics, vitamins, feed additives, and diagnostic products in poultry production. Equipment manufacturing industries producing cages, feeders, incubators, hatchery systems, and ventilation equipment have similarly expanded. Poultry litter and manure contribute to sustainable agriculture by serving as nutrient-rich organic fertilizers. In some regions, poultry waste is also utilized for biogas generation and organic farming systems.

EXPORT POTENTIAL AND INTERNATIONAL TRADE

India's poultry sector possesses substantial export potential due to increasing production capacity and competitive production costs. Poultry exports contribute valuable foreign exchange earnings and improve India's position in global agricultural trade. India exports table eggs, egg powder, processed poultry meat, breeder stock, and other poultry products to several countries including Oman, Sri Lanka, the United

Arab Emirates, and neighbouring Asian nations. According to KNN India (2024), India achieved poultry exports worth USD 184.58 million during 2023-24, representing a significant increase over previous years. Egg powder exports are particularly promising because of their long shelf life and industrial applications. Processed poultry products also hold significant export opportunities if India continues strengthening food safety standards and processing infrastructure. To compete effectively in international markets, India must continue improving disease surveillance systems, residue monitoring, quality assurance, and compliance with international sanitary standards.

Figure 3. Integrated poultry value chain and export potential of India: Comprehensive illustration of the poultry value chain including feed production, hatcheries, poultry farms, processing units, cold chain transport, retail marketing, and international exports contributing to India's economic growth.

CHALLENGES

Despite rapid growth, the Indian poultry industry faces several major challenges. Disease outbreaks such as avian influenza remain significant threats capable of causing severe economic losses and trade restrictions. Feed cost fluctuations are another major concern because feed accounts for approximately 65-70% of total production costs. Variations in maize and soybean prices directly affect profitability, particularly for small-scale farmers. Environmental sustainability and waste management have also become important issues. Large-scale poultry operations generate significant quantities of waste that require proper disposal and management to minimize environmental pollution. Market price volatility frequently affects poultry producers due to fluctuations in demand and supply. Antimicrobial resistance associated with indiscriminate antibiotic use is another emerging concern requiring sustainable disease management practices. Climate change may further influence poultry production through heat stress, altered disease patterns, and reduced feed crop yields. Therefore, climate-resilient poultry production systems are becoming increasingly important.

GOVERNMENT INITIATIVES AND POLICY SUPPORT

The Government of India has implemented several schemes and policies to promote poultry development and strengthen rural livelihoods. Programs under the Department of Animal Husbandry and Dairying support poultry entrepreneurship, infrastructure development, breed improvement, and disease control. Backyard poultry development programs have been particularly important for tribal and economically weaker regions. Distribution of improved dual-purpose birds has enhanced both income generation and nutritional security. The National Livestock Mission provides support for feed and fodder development, infrastructure creation, skill development, and capacity building. Veterinary healthcare services and vaccination campaigns further contribute to improved poultry health management. Government investment in cold chain infrastructure, modern slaughterhouses, and food processing facilities has strengthened the poultry value chain and improved food safety standards.

FUTURE PROSPECTS OF THE INDIAN POULTRY INDUSTRY

The future outlook for the Indian poultry industry remains highly promising due to rising population, urbanization, increasing incomes, and growing awareness regarding protein-rich diets. Demand for eggs and poultry meat is expected to increase significantly in the coming decades. Processed and value-added poultry products are likely to experience rapid growth due to changing consumer lifestyles and increasing demand for convenience foods. Technological innovations such as precision farming, biotechnology, artificial intelligence, and automated management systems may further improve production efficiency. Expansion of export-oriented production systems, cold chain networks, and processing facilities can position India as a major global poultry exporter. Sustainable production practices and environmentally responsible management systems will become increasingly important in the future.

CONCLUSION

The poultry sector occupies a pivotal position within India’s agricultural and economic framework. Its contributions extend far beyond egg and meat production to include employment generation, poverty alleviation, nutritional improvement, women empowerment, agricultural commercialization, technological advancement, and export earnings. The sector plays a vital role in ensuring affordable access to high-quality animal protein while simultaneously generating stable income opportunities for millions of rural households. Strong interconnections with feed manufacturing, veterinary pharmaceuticals, transportation, food processing, and retail industries further amplify its economic importance. Although challenges such as disease outbreaks, feed price fluctuations, environmental concerns, and market volatility persist, the future growth potential of the poultry industry remains substantial. Continued policy support, technological modernization, infrastructure development, and sustainable production practices will be critical for maintaining long-term growth and global competitiveness. In conclusion, the poultry industry is not merely a subsidiary agricultural activity but a major catalyst for inclusive economic development in India. Its role in strengthening food security, enhancing livelihoods, promoting nutritional well-being, and stimulating industrial growth establishes it as one of the foundational pillars of a prosperous and economically vibrant India

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How to cite:

Sharma, A., Kumar, A. M. and Sharma, M. (2026). India's poultry revolution: Growth, opportunities, and economic impact. Leaves and Dew Publication, New Delhi 110059. *Agri Journal World* 6 (2): 66-74.

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AGRI JOURNAL WORLD
VOL. 6 ISSUE 2 APRIL-JUNE, 2026

CLIMATE RESILIENCE INDICES FOR AGRICULTURE

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ABSTRACT

Climate change increasingly threatens agriculture through droughts, floods, heatwaves, and other extreme events, making resilience assessment essential for sustainable food production. Climate resilience indices evaluate the capacity of agricultural systems to anticipate, withstand, adapt to, and recover from climate-related stresses. This review discusses the concepts, methodologies, and key dimensions of resilience, including exposure, vulnerability, adaptive capacity, and recovery. It also highlights the role of remote sensing, artificial intelligence, machine learning, and scenario planning in strengthening resilience assessment, supporting evidence-based adaptation, resource allocation, and sustainable agricultural development.

KEYWORDS: Adaptive capacity, artificial intelligence, climate adaptation, climate change, Climate resilience, remote sensing, resilience indices, vulnerability

INTRODUCTION

Climate change poses significant challenges to agricultural systems through increasing temperatures, erratic rainfall, droughts, floods, and other extreme events. These challenges affect crop production, livestock systems, natural resources, and rural livelihoods. Climate resilience indices have emerged as important tools for assessing the ability of agricultural systems to withstand, adapt to, and recover from climate-related shocks and stresses.

Resilience indices provide a quantitative framework for evaluating climate risks and adaptive responses across different agricultural systems and regions. They support decision-making by identifying vulnerable areas, assessing adaptation capacity, guiding investments, strengthening early-warning systems, and monitoring long-term resilience trends. By integrating climatic, environmental, and socio-economic indicators, resilience indices help policymakers and practitioners develop effective climate adaptation strategies.

CONCEPTUAL FRAMEWORK OF AGRICULTURAL RESILIENCE

Agricultural resilience refers to the capacity of a farming system to anticipate, prepare for, respond to, and recover from climate-related disturbances while maintaining essential functions and productivity. Four major dimensions form the foundation of resilience assessment:

EXPOSURE: Exposure represents the degree to which agricultural systems experience climate hazards such as droughts, floods, heatwaves, and storms. Areas frequently affected by extreme climatic events generally face higher exposure levels.

VULNERABILITY: Vulnerability reflects the susceptibility of agricultural systems to damage caused by climate hazards. Factors such as poor infrastructure, degraded soils, limited irrigation, and economic constraints increase vulnerability.

ADAPTIVE CAPACITY: Adaptive capacity refers to the ability of farmers and institutions to adjust to changing climatic conditions. Access to technology, financial resources, education, extension services, and climate information contributes significantly to adaptive capacity.

ADAPTIVE PERFORMANCE: Adaptive performance evaluates how effectively a system responds to climatic disturbances and how quickly it recovers after a shock. Recovery time and maintenance of productivity are common indicators of adaptive performance.

Together, these four dimensions provide a comprehensive understanding of agricultural resilience and climate risk.

COMPONENTS OF CLIMATE RESILIENCE INDICES

Climate resilience indices combine multiple indicators that represent environmental, social, economic, and institutional conditions. These indicators help assess resilience at plot, farm, regional, and national scales.

The primary components include:

- Climate exposure and hazard frequency.
- Vulnerability factors affecting agricultural production.
- Adaptive capacity indicators.
- Recovery and performance measures.
- Socio-economic and environmental conditions.

Assessment across multiple scales allows researchers to identify local vulnerabilities while also understanding broader regional patterns. Such analyses support targeted adaptation planning and resource allocation.

METHODOLOGICAL APPROACHES

The development of resilience indices generally follows a structured methodology involving data collection, indicator selection, weighting, modelling, and evaluation.

Data Collection: Reliable data are essential for resilience assessment. Common sources include meteorological records, agricultural statistics, remote sensing products, socio-economic surveys, and international databases such as those maintained by the World Bank, FAO, and UN agencies.

High-quality data should be accurate, representative, and available over sufficiently long periods to capture both normal and extreme climatic conditions.

INDICATOR SELECTION: Indicator selection is one of the most critical stages in index construction. Indicators should be scientifically valid, measurable, relevant to climate resilience, and suitable for the local context.

Examples include:

- Frequency of droughts and floods.
- Access to irrigation.
- Soil quality indicators.
- Crop diversity.
- Household income.
- Education levels.
- Availability of agricultural extension services.

The selected indicators should collectively capture the multidimensional nature of resilience.

WEIGHTING AND AGGREGATION: Indicators are commonly normalized and combined into composite indices using weighting schemes. Equal weighting, expert judgement, statistical methods, and multivariate techniques are often applied depending on data availability and study objectives.

UNCERTAINTY AND SENSITIVITY ANALYSIS: Because resilience indices depend on numerous indicators and assumptions, uncertainty analysis is essential. Sensitivity analysis evaluates how changes in specific indicators influence final resilience scores. These approaches improve transparency and reliability in decision-making.

SPATIAL AND TEMPORAL DIMENSIONS

Resilience assessment requires consideration of both spatial and temporal scales.

SPATIAL SCALE: Climate resilience can be evaluated at several levels:

- Plot level
- Farm level

- Community level
- Regional level
- National level

The choice of scale depends on study objectives and data availability. Farm-level assessments provide detailed insights into management practices, while regional analyses support policy development and resource allocation.

TEMPORAL SCALE: Resilience is dynamic and changes over time. Longitudinal assessments track variations in exposure, vulnerability, adaptive capacity, and performance across years or decades.

Trend analysis helps identify whether agricultural systems are becoming more resilient or more vulnerable under changing climatic conditions. Historical observations combined with future climate projections provide valuable information for long-term planning.

CLIMATE RISK DOMAINS AND INDICATOR CATEGORIES

Climate resilience indices typically organize indicators into climate risk domains that capture different dimensions of agricultural vulnerability and adaptation.

EXPOSURE AND HAZARD FREQUENCY: Climate hazards are the primary drivers of agricultural risk. Important indicators include:

- Drought frequency.
- Rainfall variability.
- Heatwave occurrence.
- Flood incidence.
- Storm intensity.

Historical observations and climate model projections are frequently used to estimate changing hazard patterns and return periods.

VULNERABILITY: Vulnerability indicators describe the susceptibility of farming systems to climate impacts. Common indicators include:

- Dependence on rainfed agriculture.
- Soil degradation.
- Water scarcity.
- Poverty levels.
- Limited market access.

Reducing vulnerability is a central objective of climate adaptation policies.

ADAPTIVE CAPACITY: Adaptive capacity indicators assess the resources available for managing climate risks. These may include:

- Irrigation infrastructure.
- Access to credit.
- Agricultural extension services.
- Climate information systems.
- Farmer education and training.
- Crop diversification.

Higher adaptive capacity generally improves resilience and reduces long-term climate risks.

ADAPTIVE PERFORMANCE AND RECOVERY: Performance indicators evaluate how effectively agricultural systems recover from climatic disturbances. Important measures include:

- Recovery time after droughts or floods.
- Yield stability.
- Income recovery.
- Resource regeneration.

Systems capable of rapid recovery are generally considered more resilient.

EMERGING TECHNOLOGIES AND FUTURE DIRECTIONS

Recent technological developments are transforming resilience assessment and monitoring.

REMOTE SENSING APPLICATIONS: Satellite observations provide continuous information on vegetation health, land use, soil moisture, crop conditions, and environmental changes. Remote sensing supports large-scale resilience assessments, especially in regions where ground observations are limited.

Modern satellite systems such as Sentinel and Landsat offer high-resolution data useful for monitoring agricultural conditions and climate impacts.

ARTIFICIAL INTELLIGENCE AND MACHINE LEARNING: Artificial intelligence (AI) and machine learning techniques enhance the analysis of complex climate and agricultural datasets. These technologies can identify hidden patterns, improve prediction accuracy, and support early-warning systems.

Applications include:

- Drought prediction.
- Crop yield forecasting.
- Climate risk mapping.
- Land-use classification.

- Decision-support systems.

The integration of AI with remote sensing is creating new opportunities for near-real-time resilience monitoring.

SCENARIO PLANNING AND FLEXIBLE GOVERNANCE: Future climate conditions remain uncertain, making adaptive governance increasingly important. Scenario planning allows policymakers to evaluate multiple future pathways and test the effectiveness of adaptation strategies under different climate conditions.

Flexible governance systems can adjust policies as new information becomes available, reducing risks associated with uncertainty. Such approaches support long-term agricultural sustainability and climate resilience.

Climate resilience indices are becoming essential tools for evaluating agricultural vulnerability, adaptive capacity, and recovery potential under climate change. By integrating exposure, vulnerability, adaptive capacity, and performance indicators, these indices provide valuable insights for researchers, policymakers, and development practitioners. Advances in remote sensing, artificial intelligence, and climate modelling are further strengthening resilience assessment frameworks. As climate risks continue to intensify, resilience indices will play an increasingly important role in guiding adaptation investments, supporting sustainable agricultural development, and enhancing food security across diverse agricultural systems.

CONCLUSION

Climate resilience indices provide a valuable framework for assessing the capacity of agricultural systems to withstand, adapt to, and recover from climate-related shocks and stresses. By integrating key dimensions such as exposure, vulnerability, adaptive capacity, and adaptive performance, these indices enable a comprehensive understanding of climate risks and resilience levels across different agricultural contexts. Their application supports evidence-based decision-making, prioritization of adaptation investments, and development of effective climate-resilient agricultural policies. Advances in remote sensing, artificial intelligence, and climate modeling are further enhancing the accuracy and usefulness of resilience assessments. As climate change continues to affect global agriculture, resilience indices will play an increasingly important role in strengthening food security, promoting sustainable agricultural development, and improving the adaptive capacity of farming communities.

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How to cite:

Chinchorkar, S. S. (2026). Climate resilience indices for agriculture. Leaves and Dew Publication, New Delhi 110059. *Agri Journal World* 6 (2): 75-82.

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www.journalworlds.com
AGRI JOURNAL WORLD
VOL. 6 ISSUE 2 APRIL-JUNE, 2026

BACTERIOCINS: A SAFE BIOPRESERVATIVES

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ABSTRACT

The growing threat of antimicrobial resistance has intensified the search for alternatives to conventional antibiotics. Antimicrobial peptides (AMPs) are natural bioactive molecules with broad-spectrum activity against pathogenic microorganisms. Among these, bacteriocins produced by lactic acid bacteria (LAB) are recognized as safe and effective natural food preservatives. They inhibit microbial growth primarily through membrane disruption. Well-known bacteriocins, such as nisin and pediocin, are widely used in food preservation. Owing to their antimicrobial efficacy, safety, and minimal effects on food quality, AMPs and bacteriocins offer promising solutions for enhancing food safety and combating antimicrobial resistance.

KEYWORDS: Antimicrobial peptides, antimicrobial resistance, bacteriocins, food preservation, lactic acid bacteria

INTRODUCTION

The rapid emergence and global spread of antimicrobial resistance (AMR) has become a serious threat to public health and food safety. The widespread and indiscriminate use of antibiotics in human medicine, veterinary practice, and food production has accelerated the evolution of multidrug-resistant microorganisms, reducing the effectiveness of conventional antimicrobial therapies. Therefore, there is an urgent need to find safe, effective, and sustainable alternatives to antibiotics that can control pathogenic microorganisms while minimizing the development of resistance. Among the various alternatives explored, antimicrobial peptides (AMPs) have attracted considerable attention because of their broad-spectrum antimicrobial activity, rapid mode of action, and lower propensity for inducing resistance. These naturally occurring peptides are an essential component of the innate immune system and are widely distributed across bacteria, plants, insects, amphibians, marine organisms, and mammals. Most AMPs are small, cationic, amphipathic molecules that exert their antimicrobial effects by disrupting microbial cell membranes or interfering with essential intracellular processes. Their activity extends against a wide range of microorganisms, including Gram-positive and Gram-negative bacteria, fungi, viruses, and certain parasites.

This article reviews the characteristics, classification, mechanisms of action, and applications of antimicrobial peptides, with particular emphasis on bacteriocins produced by lactic acid bacteria. It also highlights their potential as natural alternatives to conventional antibiotics and chemical preservatives in addressing the growing challenge of antimicrobial resistance while promoting safer and more sustainable food preservation strategies.

ANTIMICROBIAL PEPTIDES: AN ALTERNATIVE TO ANTIBIOTICS

It is the fate of all antibacterials to be fought off by the pathogens they target. The continuous and indiscriminate use of antibiotics has resulted in multi-resistant bacterial strains all over the world. The alarming emergence of resistance among bacteria has led the World Health Organization (WHO) to announce antimicrobial resistance as a main concern (WHO, 1995). For the food microbiologist, there is no doubt that it is necessary to avoid the distribution of bacteria with mobilizable antibiotic resistances (WHO, 1995). There is a lack of efficient and safe preservatives in the food industry. Over the years, massive use of common food safety barriers led to the development of resistance by various food microorganisms. Enteric bacteria are especially tolerant to adverse environmental conditions such as low pH and high salt concentrations, which limits efficiency of some preservation methods.

Consumers demand for natural, preservative-free and minimally processed foods and worldwide concern regarding disease outbreaks caused by food-related pathogens have created a need for development of new classes of antimicrobial agents. The priority for the next decades should be focused in the development of alternative drugs and/or the recovery of natural molecules that would allow the consistent and proper control of pathogen-caused diseases. Ideally, these molecules should be as natural as possible, with a wide range of action over several pathogens and easy to produce. The discovery of two classes of antimicrobial peptides, non-ribosomally synthesized and ribosomally synthesized peptides, of wider distribution present in bacteria, insects, amphibians, crustaceans and other eukaryotes and plants - provided a new therapeutic strategy to fight microorganisms. These are termed “natural antibiotics”, because they are active against a large spectrum of microorganisms, including bacteria, filamentous fungi, protozoan and metazoan parasites (Liu *et al.*, 2000; Vizioli and Salzet, 2003). AMPs are often produced as closely related multi-member families that may vary only in a few amino acid residues (Nicolas and Mor, 1995). Despite the enormous variety of sequences and structures, AMPs possess certain common features. They are usually made of less than 50 amino acids, bear a net positive charge due to an excess of basic (often lysine and/or arginine) over acidic residues, and contain about 50% hydrophobic amino acids. They often fold into 3-dimensional amphipathic structures stabilized by cysteine disulphide bridges. Linear peptides lacking cysteines tend to fold, only upon contact with membranes, into a variety of amphipathic helices, pleated-sheets, loops, or less defined extended structures in which positively charged hydrophilic domains are well delineated from hydrophobic domains. These features seem to be the main factors affecting their known and diverse biological activities.

BACTERIOCINS FROM LAB

Lactic acid bacteria (LAB) are industrially important organisms because of their fermentative ability as well as health and nutritional benefits. Moreover, they are generally regarded as safe for incorporation into food products (Gasser, 1994). The ability of lactic acid bacteria to inhibit the growth of various Gram positive and/or Gram-negative bacteria is well known and attributed to the production of organic acids such as lactic acid and acetic acid, hydrogen peroxide, bacteriocins, bacteriocin like substances and possibly biosurfactants. Bacteriocins are ribosomally synthesized, extracellular peptides/proteins produced by bacteria, exhibiting bacteriostatic or bactericidal activity against closely related bacteria. Bacteriocin producing species have been identified among all the genera that comprise the LAB including *Lactococcus*, *Lactobacillus*, *Pediococcus*, *Leuconostoc* and *Carnobacterium* (Klaenhammer, 1998). Consumers have been consistently concerned about possible adverse health effects from the presence of chemical additives in their foods. As a result, consumers are drawn to natural and “fresher” foods with no chemical preservatives added. This perception, coupled with the increasing demand for minimally processed foods with long shelf life, has stimulated research interest in finding natural but effective preservatives such as bacteriocins. Bacteriocins, produced by LAB, may be considered natural preservatives or bio preservatives that fulfil these requirements. Klaenhammer (1993) observed that bacteriocins might take many forms and elicit bactericidal activity beyond species that are closely related to or confined within the same ecological niche. Bacteriocins are ribosomally synthesised, and because of their proteinaceous nature, bacteriocins are synthesised via a common ribosomal biosynthesis mechanism involving transcription and translation. Bacteriocins kill their target by causing dissipation of Proton Motive Force (PMF) and leakage of small intracellular substances through pore formation in the cell membrane of sensitive bacteria. Most characterised bacteriocins are heat stable, nontoxic and susceptible to degradation by proteolytic enzymes present in the gastrointestinal tract (Abrioul *et al.*, 2003).

Based on common elements, bacteriocins are classified into four well defined classes (Klaenhammer, 1988).

1. Class I bacteriocins (lantibiotics): These are post-translationally modified to contain amino acids such as lanthionine and β-methyllanthionine and several dehydrated amino acids so they are called lantibiotics. They are further divided into two subgroups A and B, based on structural features and their mode of killing.

a. Type A lantibiotics: Leader peptides are cleaved by a serine protease. They kill the target cell by depolarising the cytoplasmic membrane. Type A lantibiotics are linear and larger than type B lantibiotics and range in size from 21 to 38 amino acids. Nisin is the best-known and best-studied Gram-positive bacteriocin and has been approved as a food additive by the FDA.
b. Type B lantibiotics have a more globular secondary structure and are smaller than type A (the largest is 19 amino acids in length). Leader peptides are cleaved by an ABC transporter. Type B lantibiotics function through enzyme inhibition. Thus, mersacidin interferes with cell wall biosynthesis.

2. Class II bacteriocins (small heat-stable non-lantibiotics): These are small, heat-stable, non-lanthionine-containing peptides, not post-translationally modified, ranging in size from 30 to 60 amino acids, and they are usually positively charged at neutral pH. They are divided into four subgroups:

I. Class IIa (pediocin-like bacteriocins with a strong antilisterial effect) is the largest group, and its members are distinguished by a conserved amino-terminal sequence YGNGV[YSTH]C[X4]C and a shared strong inhibitory activity against *Listeria*. Because of their effectiveness against the food pathogen *Listeria*, class IIa bacteriocins are currently attracting much interest as potential natural and non-toxic food preservatives. Like type A lantibiotics,
Class IIa bacteriocins act through the formation of pores in the cytoplasmic membrane. Examples include Pediocin PA-1 and pediocin AcH (*Pediococcus acidilactici)*, sakacins A and P (*L. sakei*), leucocin A *(Leuconostoc gelidum)*, enterocins A and P (*E. faecium*), and carnobacteriocin (*Carnobacterium sp*.).
Class IIa bacteriocins (pediocin-like bacteriocins) are active against *Listeria* spp., and comprise the largest and most studied group.

II. Class IIb (bacteriocins whose activity depends on the complementary activity of two peptides). These form pores composed of two different peptides in the membrane of their target cells. This group includes lacticin F and lactococcin G.

III. Class IIc (sec-dependent secreted bacteriocins) includes bacteriocins that are sec-dependent, such as acidocin B and enterocin P, which can be included in both class IIa and class IIc.

IV. Class IId includes other bacteriocins such as lactocin A and B.

3. Class III bacteriocins**:** These are large heat-labile proteins. They include helveticins J and V and lactacin B.

4. Class IV bacteriocins (cyclic peptides)**:** These require lipid or carbohydrate moieties for their activity. Little is known about the structure and function of this proposed class. The group has yet to be confirmed by purification and biochemical characterization. These bacteriocins include leuconocin S and lactocin 27.

Interest has been resurgent for research on bacteriocins in the last few decades for application as natural biopreservatives. Bacteriocins are non-toxic because of their inactivation by human digestive tract proteases. In addition, no flavor or textural changes are associated with their use as biopreservatives in different food systems. Bacteriocins have attracted scientific attention in recent years not only as promising safe and natural food additives but also as potential chemotherapeutic agents. The original and most intensively studied, lantibiotic, "nisin" (a bacteriocin produced from *Lactococcus lactis*) has a long record of safe use. It has been approved by US Food and Drug Administration FDA (Food and Drug Administration, 1988) and is one of only few bacteriocins to have been applied commercially. It has antibacterial activity against many Gram-positive bacteria including food-borne pathogens such staphylococci, bacilli, clostridia and mycobacteria. Currently it is used as food preservative in more than 40 countries worldwide (Delves-Broughton, 1990). The use of pediocin PA-1 is covered by several Europe and US patents (Boudreaux and Matrozza 1992; Vandenbergh *et al*., 1989). Both nisin and pediocin PA-1 have applications in dairy and canned products. Recently Hidalgo (2007) showed that Enterocin AS-48, a bacteriocin from *Enterococcus faecalis* AS-48 is very stable with respect to pH and temperature and has a broad action spectrum against numerous bacteria, including pathogenic bacteria transmitted by food, which makes it a suitable molecule for use as a biopreservatives.

CONCLUSION

Antimicrobial peptides, particularly bacteriocins produced by lactic acid bacteria, have emerged as promising natural alternatives to conventional antibiotics and chemical food preservatives. Their broad-spectrum antimicrobial activity, safety, heat stability, and susceptibility to degradation by digestive enzymes make them attractive candidates for food preservation and therapeutic applications. With the rapid rise of antimicrobial resistance and increasing consumer demand for minimally processed, preservative-free foods, bacteriocins offer an effective and sustainable approach to enhancing food safety and quality. Although nisin and a few other bacteriocins have already achieved commercial success, continued research is needed to discover novel antimicrobial peptides, improve their production, and expand their applications. Overall, antimicrobial peptides represent a valuable strategy for combating foodborne pathogens and addressing the global challenge of antibiotic resistance.

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How to cite:

Meena, S., Jasmin, F. A. T. and Kumar, S. (2026). Bacteriocins: A safe biopreservatives. Leaves and Dew Publication, New Delhi 110059. *Agri Journal World* 6 (2): 83-89.

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AGRI JOURNAL WORLD
VOL. 6 ISSUE 2 APRIL-JUNE, 2026

NUTRITIONAL YIELD GAP IN INDIAN STAPLE CROPS: ARE WE PRODUCING ENOUGH NUTRIENTS OR JUST CALORIES?

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ABSTRACT

India is among the world's largest producers of staple crops, yet micronutrient malnutrition or "hidden hunger" remains a major challenge. This highlights the nutritional yield gap, which assesses not only crop productivity but also the supply of essential nutrients such as protein, iron, zinc, and vitamins. Factors including soil nutrient depletion, variety selection, and post-harvest losses contribute to this gap. This article examines the concept of the nutritional yield gap in Indian staple crops and discusses strategies such as biofortification, agronomic fortification, and diversified cropping systems to improve food and nutrition security.

KEYWORDS: Biofortification, food security, hidden hunger, micronutrient deficiency, nutritional yield gap, staple crops

INTRODUCTION

India's agricultural sector has achieved remarkable milestones since the Green Revolution, transforming the nation from a food-deficit country to one of the world's top grain producers. However, a fundamental question has emerged in recent years: are these vast quantities of food also delivering the nutrients that billions of people need to live healthy, productive lives? Micronutrient malnutrition - or 'hidden hunger' - affects over two billion people globally, as documented by Muthayya et al. (2013), who mapped the global distribution of deficiencies including iron, zinc, and vitamin A.

In India, the situation is deeply concerning. According to the National Family Health Survey (NFHS-5, 2019-21), about 57% of women of reproductive age and 67% of children under five years suffer from anaemia (NFHS-5, 2021). Zinc deficiency affects nearly 25% of the Indian population, and vitamin A deficiency remains a significant public health challenge in rural areas. The FAO report on global food security further underlines that despite gains in caloric availability, nutritional adequacy continues to lag behind in low- and middle-income countries, including India.

This situation reveals a critical gap - not just in food production, but in nutritional production. The concept of the 'nutritional yield gap' captures this disconnect between what our crops could deliver in terms of nutrients and what they actually do deliver to the plate. Bridging this gap requires a fundamental rethinking of how we measure, value, and manage agricultural productivity.

UNDERSTANDING THE NUTRITIONAL YIELD GAP

The traditional yield gap is defined as the difference between the potential yield of a crop (achievable under optimal conditions) and its actual farm-level yield. The nutritional yield gap extends this framework to nutrients - it is the difference between the potential nutrient output per hectare and the actual nutrient content delivered through harvested produce (Bouis and Saltzman, 2017).

For example, a wheat variety may yield 4 tonnes per hectare on a smallholder farm, while its potential yield under optimal management is 6 tonnes per hectare. But if the grain from the actual yield contains only 20 mg/kg of zinc compared to the potential of 40 mg/kg, the nutritional yield gap is enormous - both in quantity and quality dimensions (Velu et al., 2014). The dilution effect, where rapid biomass accumulation outpaces micronutrient uptake in high-yielding varieties, is a major contributor to this qualitative gap (White and Broadley, 2009).

The nutritional yield gap operates through two interconnected pathways:

- Quantitative gap: Lower total production means fewer nutrients available per capita.
- Qualitative gap: Even at potential yields, the nutrient density per unit of food may be insufficient due to variety choice, soil health, or agronomic practices.

Table 1: Estimated Nutritional Yield Gap in Major Indian Staple Crops

Crop	Nutrient	Potential (mg/kg)	Actual Farm Level (mg/kg)	Nutritional Yield Gap (%)	Primary Cause
Rice	Zinc	28-35	12-18	~50%	Soil Zn depletion, HYV varieties
Wheat	Iron	40-50	20-28	~45%	High-yielding but low Fe varieties
Maize	Protein	10-12%	6-8%	~35%	N deficiency, quality seed gap
Pulses (Lentil)	Protein	26-28%	20-22%	~22%	Poor agronomy, water stress
Sorghum	Iron	35-45	15-20	~55%	Neglect of traditional varieties
Pearl Millet	Zinc	35-45	22-28	~38%	Soil depletion, climate stress

Source: Compiled from HarvestPlus, ICRISAT, and ICAR data (2020-2024)

KEY DRIVERS OF THE NUTRITIONAL YIELD GAP

1. *Soil Nutrient Depletion*

Decades of intensive cropping without adequate replenishment of micronutrients have severely depleted Indian soils. About 49% of Indian soils are deficient in zinc, 33% in boron, and significant proportions are low in iron and manganese (Sharma et al., 2017). Since plants draw micronutrients directly from the soil, a nutrient-poor soil inevitably produces nutrient-poor grain, regardless of how high the yield appears on paper.

2. *Dominance of High-Yielding but Nutritionally Poor Varieties*

The Green Revolution prioritized yield quantity over quality. Many high-yielding varieties (HYVs) of rice and wheat, while producing more grain per hectare, contain lower concentrations of iron, zinc, and protein compared to traditional landraces. The 'dilution effect' - where rapid biomass accumulation outpaces nutrient uptake - is well documented in these varieties (White and Broadley, 2009). Velu et al. (2014) further confirmed that genetic variation for grain zinc and iron in modern wheat germplasm remains underexploited.

3. *Imbalanced Fertilization*

Indian farmers predominantly apply nitrogen (N), phosphorus (P), and potassium (K) fertilizers, often in imbalanced ratios, while micronutrient fertilization remains largely neglected. Prasad et al. (2014) demonstrated that excess nitrogen application can further dilute grain micronutrient concentrations through the dilution effect, while integrated micronutrient management significantly improves grain iron and zinc content in cereal crops.

4. *Post-Harvest Losses and Processing*

Even when nutrients are present in harvested grain, significant losses occur during storage, milling, and processing. Polishing of rice removes up to 90% of thiamine (Vitamin B1) and significant portions of iron and zinc present in the bran layers. Post-harvest losses of fruits and vegetables - which are critical micronutrient sources - exceed 30-40% in India due to poor cold chain infrastructure, compounding the nutritional yield gap before food even reaches consumers.

MEASURING THE NUTRITIONAL YIELD GAP

Quantifying the nutritional yield gap requires an interdisciplinary approach combining agronomy, nutrition science, and data analytics. The following steps are essential:

- Crop-specific nutrient benchmarking: Establishing reference values for nutrient concentrations in each crop under optimal conditions.

- Farm-level sampling: Systematic collection and analysis of grain/produce samples from representative farms across agro-ecological zones.
- Nutrient gap index (NGI): A composite index expressing actual vs. potential nutrient delivery per hectare per season.
- Dietary translation: Converting farm-level nutrient output to per capita daily nutrient availability to assess public health implications.

Table 2: Strategies to Bridge the Nutritional Yield Gap in Indian Agriculture

Strategy	Mechanism	Key Crops Targeted	Expected Benefit
Biofortification	Breeding for high nutrient density	Rice, Wheat, Maize, Lentil	20-60% increase in Fe/Zn
Agronomic fortification	Soil/foliar micronutrient application	All staple crops	15-40% increase in grain Zn/Fe
Traditional variety revival	Promoting nutritious landraces	Millets, Rice, Sorghum	Higher micronutrient density
Crop diversification	Including legumes and vegetables	Pulses, Vegetables	Improved dietary diversity
Reduced tillage + organic matter	Improving soil micronutrient availability	All crops	Better soil-plant nutrient transfer
Post-harvest fortification	Fortifying flour, rice, oil	Wheat, Rice, Oil crops	Population-level impact

BRIDGING THE NUTRITIONAL YIELD GAP: WAY FORWARD

BIOFORTIFICATION: BREEDING NUTRITION INTO SEEDS

Biofortification - the process of increasing the concentration of essential nutrients in staple crops through plant breeding, agronomic practices, or biotechnology - is among the most powerful tools for addressing the nutritional yield gap at scale. Bouis and Saltzman (2017) reviewed evidence from the HarvestPlus program (2003-2016) and conclusively demonstrated that biofortified crops can significantly reduce micronutrient deficiencies in resource-poor farming communities. Zinc-enriched wheat varieties (Zinc Shakthi), iron-enriched pearl millet, and high-zinc rice varieties are now being promoted in India, offering a sustainable, food-based solution that can reach even the most remote farming communities.

AGRONOMIC FORTIFICATION

Soil application and foliar sprays of zinc sulphate, ferrous sulphate, and other micronutrient formulations can significantly increase the nutrient density of harvested grain. Prasad et al. (2014) showed through extensive field trials that zinc sulphate application at 25 kg/ha increases grain zinc content by 20-35% while also improving crop yields in deficient soils. This integrated approach to soil and plant nutrition not only addresses the nutritional yield gap but delivers a direct productivity benefit to farmers.

MILLET REVIVAL AND CROP DIVERSIFICATION

Millets such as pearl millet (bajra), finger millet (ragi), and sorghum (jowar) are nutritionally superior to polished rice and refined wheat in terms of iron, zinc, calcium, and dietary fiber. White and Broadley (2009) highlighted that crop diversification, including integration of micronutrient-dense species into cropping systems, is one of the most effective long-term strategies for reducing dietary micronutrient gaps. India's recognition of 2023 as the International Year of Millets has renewed focus on these ancient grains, and integrating them into the public distribution system can create transformative nutritional impact.

CONCLUSION

India's agricultural success story, measured in tonnes of grain produced per hectare, masks a profound nutritional failure measured in nutrients delivered per person per day. The nutritional yield gap - the chasm between what our fields could nourish us with and what they actually do - is a critical but underappreciated challenge for food and nutrition security, as repeatedly underscored by global nutrition assessments. Addressing this gap demands a paradigm shift in how we define and measure agricultural productivity. Yield, measured purely in biomass, is no longer a sufficient metric. We must transition towards 'nutrient-sensitive agriculture' that simultaneously optimizes caloric output and micronutrient delivery. This requires coordinated action across plant breeding, soil management, agronomic practices, post-harvest systems, and food policy. The tools - biofortification, agronomic fortification, millet promotion, and crop diversification - already exist and have demonstrated efficacy. What is needed now is the political will, institutional support, and farmer awareness to deploy them at scale. Only then can India truly claim to be feeding its billion-plus population - not just in calories, but in the full spectrum of nutrients that sustain human health and dignity.

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How to cite:

Dodewar, P. G. (2026). Nutritional yield gap in Indian staple crops: Are we producing enough nutrients or just calories? Leaves and Dew Publication, New Delhi 110059. *Agri Journal World* 6 (2): 90-95.

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AGRI JOURNAL WORLD
VOL. 6 ISSUE 2 APRIL-JUNE, 2026

INSECTS AND MICROBES- A HIDDEN PARTNERSHIP

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ABSTRACT

The insect microbiome plays a crucial role in host survival, development, and adaptation. Dominated primarily by Proteobacteria and Firmicutes, gut microbial communities vary widely among insect groups such as Coleoptera and Diptera. This article highlights two major forms of mutualism: nutritional symbiosis, in which microbes aid digestion and nutrient synthesis, and defensive symbiosis, where beneficial bacteria produce antimicrobial compounds that protect hosts from pathogens. Understanding these intricate microbial interactions offers promising opportunities for advancing sustainable agriculture, biological pest management, medicine, and biodiversity conservation.

KEYWORDS: Defensive symbiosis, insect gut microbiome, nutritional symbiosis, symbiotic bacteria

INTRODUCTION

Beneath the tough outer shell of every insect lies a hidden world filled with life. This tiny universe, made up of bacteria, fungi, and other microorganisms, represents one of the most interesting partnerships in nature. The bond between insects and their microbial partners is not just about living alongside each other; it is a deeply interconnected alliance that has developed over hundreds of millions of years.

From the termite that eats wood to the honeybee that helps pollinate our crops, insects depend on their microbial partners to survive. These small allies assist in breaking down food, creating essential nutrients, protecting against diseases, and even shaping behavior. Recent advances in DNA sequencing technology have uncovered the incredible complexity of these relationships. This discovery opens up new paths for understanding insect biology and finding new ways to manage pests and promote conservation.

THE GUT MICROBIOME: A MICROSCOPIC UNIVERSE

COMPOSITION AND DIVERSITY

The insect gut microbiome is one of the most diverse microbial communities on Earth. A detailed study of 305 individual insects from 218 species and 21 taxonomic orders showed that insect gut bacteria are dominated by two main groups: Proteobacteria, which account for 62.1% of total sequences, and Firmicutes, making up 20.7%. These results, based on 16S rRNA gene sequencing, highlight the diversity and patterns in insect-microbe relationships (Yun et al., 2014).

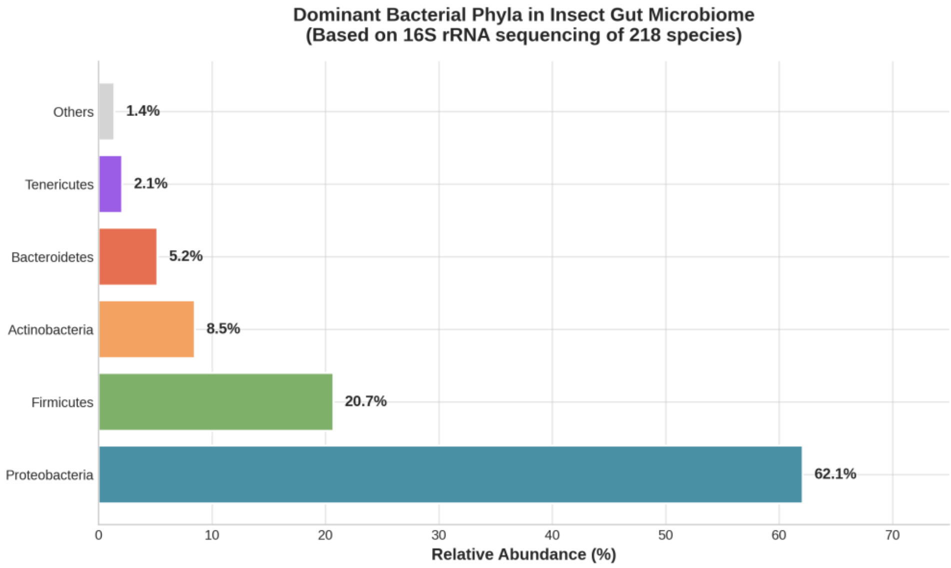

Figure 1. Dominant bacterial phyla in the insect gut microbiome based on 16S rRNA gene sequencing of 218 insect species (adapted from Yun et al., 2014).

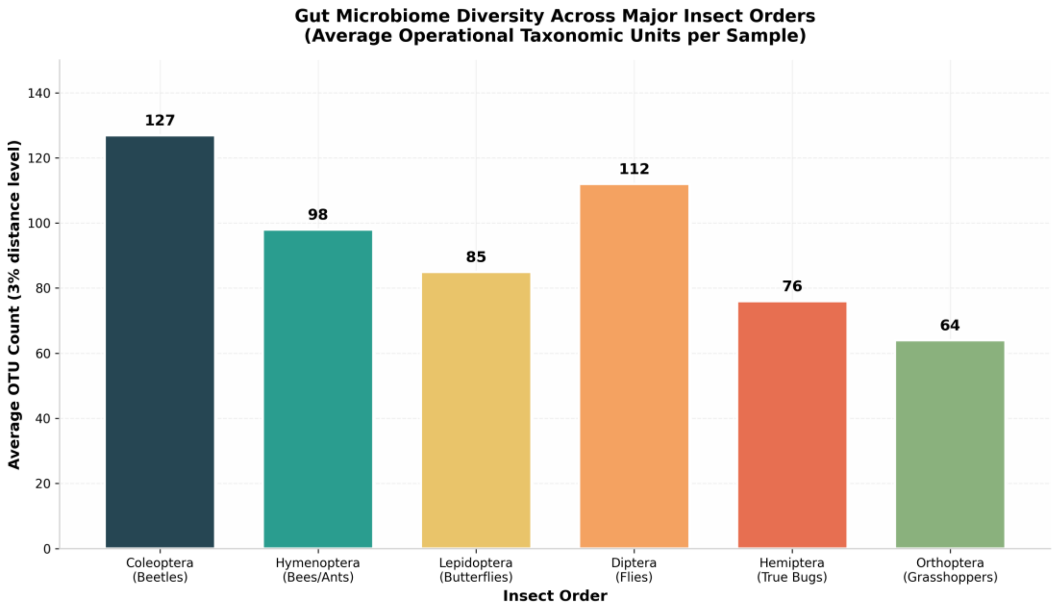

Figure 2. Gut microbiome diversity across major insect orders based on average operational taxonomic unit (OTU) counts per sample.

The makeup of the gut microbiome differs greatly among insect orders. Beetles (Coleoptera) have the highest bacterial diversity, averaging 127 operational taxonomic units (OTUs) per sample. Flies (Diptera) follow with 112 OTUs. This variation reflects the different ecological roles, diets, and evolutionary backgrounds of these insect groups.

SYMBIOTIC BACTERIA: PARTNERS IN SURVIVAL

NUTRITIONAL SYMBIOSIS

One of the most important roles of gut bacteria is nutritional support. Many insects eat diets low in essential nutrients, and their microbial partners make up for these gaps. Termites, for example, depend on a complex group of bacteria and protists to break down cellulose from wood into digestible sugars. Without these microbes, termites would starve even though they eat wood (Brune, 2014). Grain pest beetles offer another interesting example. These insects have symbiotic relationships with bacteria and yeasts that provide crucial amino acids and vitamins. Recent research at the Max Planck Institute for Chemical Ecology showed that Bacteroidetes bacteria help with cuticle production in beetles. This improves their defense against predators and helps them resist drying out (Engl et al., 2025).

DEFENSIVE SYMBIOSIS

In addition to nutrition, symbiotic bacteria act as strong protectors against pathogens and parasites. Fungus-growing ants cultivate specific bacteria from the Pseudonocardia and Streptomyces genera on their bodies. These bacteria produce antibiotics that safeguard the ants' fungal gardens from parasitic fungi, especially Escovopsis. This mutualism is one of the most advanced examples of defensive symbiosis in the animal kingdom (Chen et al., 2023).

Table 1. Examples of Defensive Symbiotic Bacteria Associated with Insects

Bacteria	**Host Insect**	**Defensive Function**
Pseudonocardia	Leaf-cutter ants	Produces antibiotics against Escovopsis
Streptomyces	Fungus-growing ants	Produces candicidin D antifungal
Burkholderia	Bean bugs	Detoxifies pesticides, primes immunity
Bacillus	Termites	Inhibits pathogenic fungi in fungus gardens
Lactobacillus	Honeybees	Stimulates an immune response against pathogens

CONCLUSION

The symbiotic relationship between insects and microorganisms represents one of nature's most remarkable and enduring partnerships. Microbial communities play essential roles in digestion, nutrient synthesis, immunity, and protection against pathogens, contributing significantly to insect survival and adaptation. Advancing insect research is enhancing our understanding of ecological and evolutionary processes while offering valuable applications in sustainable agriculture, biological pest management, medicine, and biodiversity conservation. These hidden microbial associations demonstrate that life is sustained through interconnected biological networks, emphasising the importance of symbiosis in maintaining ecosystem health and resilience.

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How to cite:
Raman, R. and Sarkar, R. (2026). Insects and microbes: A hidden partnership. Leaves and Dew Publication, New Delhi 110059. *Agri Journal World* 6 (2): 96-99.

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www.journalworlds.com
AGRI JOURNAL WORLD
VOL. 6 ISSUE 2 APRIL-JUNE, 2026

LAND CAPABILITY CLASSIFICATION FOR SUSTAINABLE LAND RESOURCE MANAGEMENT

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ABSTRACT

Land capability classification is a scientific approach for evaluating land based on soil properties, slope, erosion risk, drainage, and climatic conditions to determine its most appropriate use. It serves as a valuable tool for sustainable land resource management by guiding land-use planning, agricultural development, forestry, and conservation practices. Matching land use with its inherent capability helps improve productivity, minimize land degradation, and conserve soil and water resources. This article discusses the principles of land capability classification, conservation planning, major capability classes, and sustainable management practices that support efficient resource utilisation and long-term environmental sustainability.

KEYWORDS: Agriculture, hazards, limitation, resource, soil

INTRODUCTION

Land is one of the most valuable natural resources supporting agriculture, forestry, biodiversity, water resources, and human livelihoods. However, increasing population pressure, rapid urbanization, unsustainable farming practices, deforestation, and climate change have accelerated land degradation worldwide. Soil erosion, declining soil fertility, salinization, waterlogging, and desertification have significantly reduced the productive capacity of agricultural lands, threatening food security and environmental sustainability. Sustainable land resource management has therefore become essential for maintaining agricultural productivity while conserving natural resources for future generations.

Land resource management involves the scientific planning, evaluation, and utilization of land according to its inherent capability and limitations. Rather than using land indiscriminately, sustainable management aims to match land use with its physical characteristics to maximize productivity and minimize environmental degradation. Among the various tools available for scientific land-use planning, Land

Capability Classification (LCC) is one of the most widely accepted systems. Developed by the United States Department of Agriculture (USDA), the LCC system evaluates land based on factors such as soil properties, slope, erosion risk, drainage, climate, and other physical characteristics to determine its most appropriate use.

By identifying the strengths and limitations of different land units, land capability classification supports informed decision-making for agriculture, forestry, pasture development, watershed management, wildlife conservation, and infrastructure planning. The integration of LCC with modern technologies such as Geographic Information Systems (GIS), remote sensing, and digital soil mapping has further enhanced its accuracy and usefulness in sustainable land resource management.

CONCEPT OF LAND CAPABILITY CLASSIFICATION

Land Capability Classification is a scientific system that categorizes land according to its potential for sustained agricultural production and other appropriate land uses without causing long-term degradation. Unlike land suitability evaluation, which focuses on the requirements of a particular crop, capability classification assesses the overall productive capacity of land based on relatively permanent characteristics that are difficult or uneconomical to modify.

The system considers several physical factors, including soil depth, texture, structure, permeability, drainage, slope, erosion hazard, stoniness, salinity, and climatic conditions. These factors determine the intensity of land use that can be sustained while maintaining soil productivity and environmental quality. The fundamental principle of LCC is that land should be used according to its capability rather than attempting to overcome severe natural limitations through costly management interventions.

Land capability classification serves as an important decision-support tool for planners, farmers, policymakers, and environmental managers. It helps identify suitable areas for intensive cultivation, horticulture, agroforestry, grazing, forestry, and wildlife conservation, thereby reducing the risks of land degradation and improving resource-use efficiency.

PRINCIPLES OF LAND CAPABILITY CLASSIFICATION

The Land Capability Classification system is based on several scientific principles that ensure sustainable utilization of land resources.

Assessment of Natural Land Characteristics: Land is evaluated using relatively permanent physical attributes such as soil depth, texture, structure, drainage, slope, erosion susceptibility, climatic conditions, and water availability. These characteristics determine the productive potential of land and its limitations for agricultural use.

Matching Land Use with Land Capability: One of the fundamental principles of sustainable land management is to utilize land according to its inherent capability. Highly productive lands should be reserved for intensive agriculture, whereas fragile or marginal lands are better suited for forestry, pasture, agroforestry, or wildlife conservation.

Conservation-Oriented Management: The classification system recognizes that each land unit requires appropriate conservation measures based on its limitations. Soil and water conservation practices such as contour farming, terracing, strip cropping, cover cropping, conservation tillage, and vegetative barriers are recommended according to the capability class to minimize erosion and maintain long-term productivity.

Sustainable Resource Utilization: Land capability classification emphasizes the balanced use of natural resources by improving agricultural productivity while conserving soil, water, biodiversity, and ecosystem services. Proper land-use planning based on capability assessment reduces environmental degradation and promotes sustainable development.

COMPONENTS OF THE LAND CAPABILITY CLASSIFICATION SYSTEM

The USDA Land Capability Classification system consists of three hierarchical levels that provide increasing detail for land evaluation.

CAPABILITY CLASSES

Capability classes represent the broadest level of classification and indicate the overall suitability of land for agricultural use. The system consists of eight capability classes (I to VIII), arranged in order of increasing limitations for cultivation.

- **Class I:** These lands have very few limitations and are highly suitable for intensive cultivation. They possess deep, fertile, well-drained soils with gentle slopes and good moisture availability. Minimal conservation practices are required.
- **Class II:** These lands have moderate limitations such as gentle slopes, moderate erosion risk, or slight drainage constraints. They remain suitable for cultivation but require moderate conservation measures to maintain productivity.

- **Class III:** These lands possess severe limitations including steeper slopes, greater erosion hazards, lower soil fertility, or drainage problems. Cultivation is possible only with careful management and specialized conservation practices.
- **Class IV:** These lands have very severe limitations that considerably restrict crop production. They require intensive soil and water conservation measures, careful crop selection, and restricted cultivation.
- **Class V:** These lands are generally unsuitable for regular cultivation because of limitations such as frequent flooding, stoniness, or poor drainage rather than erosion. They are better suited for permanent pasture, grazing, forestry, or wildlife habitat.
- **Class VI:** These lands have severe limitations such as steep slopes, shallow soils, or high erosion hazards that make cultivation uneconomical. They are most appropriate for grazing, forestry, and watershed protection.
- **Class VII:** These lands possess very severe limitations that severely restrict agricultural use. Their primary uses include forest conservation, controlled grazing, watershed management, and wildlife habitat.
- **Class VIII:** These lands have limitations that preclude commercial crop production altogether. They are best reserved for recreation, biodiversity conservation, watershed protection, ecological restoration, and other environmental purposes.

The progression from Class I to Class VIII reflects increasing limitations and decreasing suitability for intensive agriculture. This classification provides a scientific basis for selecting appropriate land uses while minimizing environmental degradation and ensuring the sustainable management of natural resources.

CAPABILITY SUBCLASSES AND CAPABILITY UNITS

To provide more detailed information on land limitations, capability classes are further divided into capability subclasses and capability units. Capability subclasses identify the dominant limitation affecting land use and are represented by four symbols:

- **e (erosion):** Indicates susceptibility to soil erosion caused by water or wind.
- **w (wetness):** Represents limitations due to poor drainage, high water table, flooding, or excessive soil moisture.

- **s (soil limitations):** Includes shallow soils, low water-holding capacity, stoniness, salinity, sodicity, or low inherent fertility.
- **c (climatic limitations):** Refers to adverse climatic conditions such as low rainfall, drought, or temperature extremes that restrict agricultural use.

Within each subclass, capability units group areas having similar management requirements, productivity potential, and conservation needs. These units facilitate field-level planning by enabling the adoption of appropriate crop choices, management practices, and conservation measures for specific land conditions.

ROLE OF LAND CAPABILITY CLASSIFICATION IN SUSTAINABLE LAND RESOURCE MANAGEMENT

Land capability classification forms the foundation of sustainable land resource management by ensuring that land is utilized according to its inherent potential and limitations. Matching land use with land capability minimizes degradation while maximizing long-term productivity.

In agriculture, capability classification assists in selecting suitable cropping systems, irrigation methods, nutrient management practices, and conservation technologies. Highly productive lands are allocated for intensive crop production, whereas marginal lands are recommended for agroforestry, pasture development, horticulture, or forestry. Such scientific land-use planning improves resource-use efficiency, reduces production risks, and enhances farm sustainability.

The classification system also supports watershed management by identifying erosion-prone areas requiring soil and water conservation measures. It guides afforestation programmes, biodiversity conservation, grazing management, and restoration of degraded lands. Government agencies, planners, and researchers extensively use capability maps for regional land-use planning, infrastructure development, and natural resource conservation.

SOIL AND WATER CONSERVATION BASED ON LAND CAPABILITY

The effectiveness of soil and water conservation largely depends on adopting practices appropriate to the capability of the land. Since each capability class possesses different limitations, conservation measures should be tailored accordingly.

For Classes I and II, conservation agriculture practices such as minimum tillage, crop rotation, cover cropping, residue retention, and balanced nutrient management are generally sufficient to maintain soil productivity. In Classes III and IV, additional measures including contour cultivation, strip cropping, vegetative barriers, terracing, and controlled irrigation become necessary to minimize erosion and runoff.

For Classes V to VIII, cultivation is generally not recommended. Instead, these lands are better utilized for pasture development, silviculture, agroforestry, watershed protection, wildlife habitat, and ecological restoration. Maintaining permanent vegetation cover on these lands helps reduce erosion, improve water infiltration, enhance biodiversity, and increase carbon sequestration.

Conservation planning should also include rainwater harvesting, integrated nutrient management, efficient irrigation systems, and organic matter management to improve soil health and climate resilience.

LAND MANAGEMENT IN HILLY, ARID, AND SEMI-ARID REGIONS

Land capability classification is particularly valuable in fragile ecosystems where inappropriate land use can accelerate degradation.

Hilly Regions

Hilly regions are highly susceptible to soil erosion, landslides, and nutrient losses due to steep slopes and intense rainfall. Capability assessment helps identify suitable areas for cultivation while restricting agricultural activities on highly vulnerable slopes. Recommended conservation measures include bench terracing, contour farming, contour bunding, vegetative hedges, strip cropping, check dams, and agroforestry systems. These practices reduce runoff, improve water infiltration, stabilize slopes, and conserve soil fertility.

Arid and Semi-arid Regions

Arid and semi-arid regions face challenges such as water scarcity, wind erosion, salinity, and desertification. Land capability classification assists in selecting drought-tolerant crops, suitable irrigation systems, and sustainable land management practices. Conservation measures include shelterbelts, windbreaks, mulching, conservation tillage, rainwater harvesting, drip irrigation, and integrated watershed management. These interventions improve soil moisture conservation, reduce wind erosion, and enhance agricultural productivity under water-limited conditions.

Modern Approaches in Land Capability Assessment

Recent technological advancements have significantly improved the accuracy and efficiency of land capability assessment. Geographic Information Systems (GIS), Global Positioning Systems (GPS), remote sensing, unmanned aerial vehicles (UAVs), and digital soil mapping enable rapid collection, analysis, and visualization of spatial information.

Satellite imagery provides valuable data on land use, vegetation cover, topography, soil moisture, and erosion status over large areas. GIS integrates these datasets to generate detailed land capability maps, facilitating evidence-based land-use planning at farm, watershed, and regional scales.

Digital soil mapping combines field observations with environmental variables and machine learning techniques to predict soil properties with high spatial resolution. These technologies support precision agriculture by enabling site-specific nutrient management, irrigation scheduling, erosion risk assessment, and climate-smart land management. Their integration with decision-support systems is expected to play an increasingly important role in sustainable land resource management.

FUTURE PERSPECTIVES

Growing concerns over climate change, land degradation, and food security require greater emphasis on scientific land evaluation and sustainable land-use planning. Future land capability assessment should integrate climate projections, ecosystem services, carbon sequestration potential, and socioeconomic considerations to support resilient agricultural systems.

The application of artificial intelligence, machine learning, cloud computing, and geospatial technologies is expected to improve the precision and efficiency of capability assessment. Strengthening digital soil information systems and promoting farmer awareness regarding capability-based land management will further contribute to sustainable agricultural development.

CONCLUSION

Land capability classification provides a scientific foundation for sustainable land resource management by matching land use with its inherent potential and limitations. It enables informed decisions regarding agriculture, forestry, grazing, watershed management, and biodiversity conservation while minimizing soil degradation and resource depletion. Appropriate soil and water conservation measures based on capability classes help maintain long-term productivity, improve environmental quality, and strengthen climate resilience. The integration of modern geospatial technologies, digital soil mapping, and precision agriculture has further enhanced the effectiveness of capability assessment. Adopting land capability-based planning will play a vital role in ensuring sustainable agricultural production, efficient resource utilization, and environmental conservation for future generations.

How to cite:

Gour, N., Singh, N., Rajput, A. and Shukla, A. (2026). Land capability classification for sustainable land resource management. Leaves and Dew Publication, New Delhi 110059. *Agri Journal World* 6 (2): 100-107.

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www.journalworlds.com
AGRI JOURNAL WORLD
VOL. 6 ISSUE 2 APRIL-JUNE, 2026

OPTIMIZING SEED LONGEVITY: THE CRITICAL ROLE OF TEMPERATURE AND RELATIVE HUMIDITY

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ABSTRACT

Seed longevity is essential for agricultural productivity and the conservation of genetic resources. Temperature and relative humidity are the primary factors influencing seed viability during storage. Proper management of these conditions reduces post-harvest losses, maintains germination, and extends seed shelf life. This article discusses the scientific basis of seed longevity, physiological responses to storage conditions, and practical strategies for optimizing seed storage. It also highlights the importance of species-specific storage requirements and advances in storage technologies for preserving seed quality, supporting sustainable agriculture, and safeguarding germplasm for future breeding programs.

KEYWORDS: Relative humidity, seed longevity, seed storage, temperature, viability

INTRODUCTION

Crop production and plant biodiversity are based on seeds. Both commercial agriculture and germplasm conservation depend on their ability to remain viable over time. Genetic characteristics, moisture content, storage temperature, and relative humidity are some of the variables that affect seed longevity, or the amount of time that seeds maintain their ability to germinate. The rate of loss of vigour and viability of orthodox seeds depends mainly on the temperature where the seed is stored and the moisture content of the seed (Corbineau, F., 2024). Since temperature and relative humidity are the most controllable of these, they are essential tools for managing seed storage.

TEMPERATURE'S EFFECT ON SEED LONGEVITY

The metabolic rate of seeds is directly impacted by temperature. Lipid peroxidation, enzyme inactivation, and deterioration occur more quickly at higher temperatures because they speed up respiration and biochemical reactions. On the other hand, lower temperatures prolong seed viability by slowing these metabolic processes.

- Optimal storage temperatures vary by species but generally range from **0–15°C** for most orthodox seeds.
- Sub-zero storage (e.g., -18°C) is used for long-term conservation in seed banks.
- High temperatures, especially above 30°C, dramatically reduce seed longevity.

INFLUENCE OF RELATIVE HUMIDITY ON SEED STORAGE

The seed moisture content, which is directly related to physiological stability, is influenced by relative humidity. Seeds adjust to the relative humidity of their surroundings, and elevated relative humidity can lead to moisture absorption, which can encourage the growth of fungi, activate enzymes, and ultimately reduce germination, which deteriorates the seed and reducing the longevity. Seed aging causes internal DNA damage during storage that ultimately leads to viability decline (Waterworth *et al.*,2024) throughout the storage duration. Hence, seeds when stored in high relative humidity or moisture conditions age quickly, ultimately leading to less vigour seeds which fail to perform better under field conditions (Lohitha *et al*.,2024). But with proper management of relative humidity and moisture content of seeds during the storage period, seed quality can be maintained.

For orthodox seeds, a moisture content of 5–8% is ideal for long-term storage.

- Low RH environments (10–30%) reduce water activity, minimizing metabolic degradation.
- Moisture-proof packaging, desiccants, and humidity-controlled storage chambers are effective strategies.

Pic 1. Humidity-controlled storage chambers

INTERACTION BETWEEN TEMPERATURE AND RELATIVE HUMIDITY

Temperature and RH do not act independently. Their interaction determines the overall seed deterioration rate, commonly described by Harrington's "Seed Viability Equation", which states that every 1% decrease in seed moisture or 5°C decrease in storage temperature roughly doubles the seed's storage life (only applicable to orthodox seeds).

- **Cool and dry conditions** are universally optimal for orthodox seeds.
- **Tropical storage challenges:** High ambient temperatures and humidity require additional control measures like sealed containers, silica gel, or cold rooms.
- **Seed type considerations:** Recalcitrant seeds are sensitive to desiccation and cannot tolerate conventional low-moisture storage, requiring alternative approaches, rather like orthodox seeds.

TECHNIQUES FOR INCREASING THE LIFESPAN OF SEEDS

1. **Pre-storage Conditioning**: Make sure the seeds are thoroughly cleansed and dried.
2. **Moisture Control**: Make use of desiccants and packaging that can withstand moisture.
3. **Temperature Control**: Keep seeds at constant, low temperatures that are appropriate for their species.
4. **Consistent Monitoring**: Evaluate viability by testing germination rates on a regular basis.

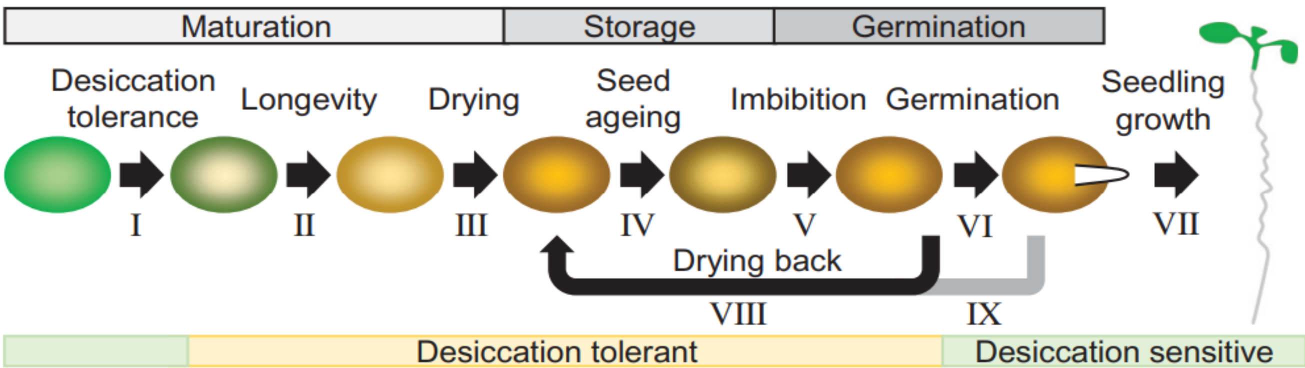

Figure 1: Series of stages showing how seed priming helps in improving seed longevity

(*taken from Wanda Waterworth et al.,2024*)

5. **Utilizing Controlled Atmospheres**: Storage that is vacuum-packed or nitrogen-flushed lessens oxidative damage.
6. **Seed Priming**: While some treatments can enhance storage performance, they must be carefully managed to prevent early deterioration.

Commercially seed priming technologies hydrate seeds first, following a dry back, to assist cellular repair and to improve the germination vigour and seedling growth (Fabrissin *et al*., 2021; Pagano *et al*.,2023). The figure below represents the important stages of seed from maturation to seedling establishment and how priming helps in improving longevity.

Here desiccation tolerance is lost as seeds progress to germination, but can be re-established by treatment with ABA or PEG (IX), allowing survival after re-drying (Zinsmeister *et al.*,2021).

CONCLUSION

Seed longevity is dependent on a complex interaction of genetic and environmental factors. The two most variable of them are temperature and relative humidity, making them crucial instruments for controlling seed storage. Adjusting moisture with the use of sealed containers, silica gel, or moisture-regulating chambers, and using crop-specific temperatures helps in increasing the seed longevity and reducing seed deterioration, thus preserving seed shelf life for a longer period of time. Along with these practices, research focused on preservation of germplasm in seed banks (long-term ageing) and stresses associated with short-term ageing, representing variable environmental conditions, should be given prime importance, which not only helps in improving seed longevity but also helps in maintaining the quality for a longer duration.

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www.journalworlds.com
AGRI JOURNAL WORLD
VOL. 6 ISSUE 2 APRIL-JUNE, 2026

AQUAPORINS IN MAMMARY GLAND: EVOLVING TALE OF MASTOLOGY

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ABSTRACT

Aquaporins (AQPs) are membrane channel proteins that regulate water and small solute transport and are widely expressed in the mammary gland. Beyond maintaining fluid balance and lipid transport, aquaporin isoforms, including AQP1, AQP3, AQP4, AQP5, and AQP7, contribute to breast cancer progression by influencing cell proliferation, migration, invasion, angiogenesis, and epithelial–mesenchymal transition. Their expression is associated with tumor aggressiveness, microenvironment remodeling, and patient prognosis. Aquaporins show promise as diagnostic and prognostic biomarkers and potential therapeutic targets, although selective clinical inhibitors remain under development.

KEYWORDS: Aquaporins, biomarkers, breast cancer, mammary gland, tumor microenvironment

INTRODUCTION

Aquaporins (AQPs) are a family of small transmembrane channel proteins traditionally recognized for enabling rapid water transport across cell membranes, yet in mammary tissue they also govern glycerol and solute movement, thereby influencing local fluid balance and lipid metabolism. Over the past decade, studies in breast biology and oncology have shown that several aquaporin isoforms—particularly AQP1, AQP3, AQP4, AQP5 and AQP7—undergo a transition from purely physiological roles in the mammary gland to active modulation of cancer hallmarks, including proliferation, migration, invasion, angiogenesis and metastatic dissemination. Isoform- and cell-type-specific expression and localization patterns in endothelial cells, epithelial compartments, stromal fibroblasts and adipocytes have been correlated with tumor aggressiveness, remodelling of the tumor microenvironment and patient prognosis, positioning aquaporins as promising diagnostic and prognostic biomarkers as well as emerging therapeutic targets in breast cancer. In this article, we review the structural and functional characteristics of mammary aquaporins, delineate isoform-specific contributions to breast cancer progression and tumor–stroma crosstalk, and discuss current advances and remaining challenges in harnessing aquaporin-based strategies for early detection, risk stratification and targeted therapy in mastology.

AQUAPORINS

Aquaporins are small transmembrane proteins that form channels allowing water to move rapidly in and out of cells. They share a conserved structure: each aquaporin monomer has six alpha-helical segments crossing the cell membrane and two loops that fold into the membrane to form a narrow pore, and four monomers come together to form a functional tetramer. Functionally, aquaporins fall into two main groups. Water-selective aquaporins mainly transport water, while aquaglyceroporins also conduct glycerol and other small neutral solutes such as urea and some gases. This transport capacity is critical for processes like urine concentration, fat metabolism, brain water balance, and general cellular homeostasis.

At the molecular level, several structural motifs fine-tune channel function. Highly conserved NPA (Asn–Pro–Ala) motifs meet in the middle of the pore to control water permeability, while the aromatic/arginine (ar/R) region near the extracellular side acts as a selectivity filter based on size and charge. Changes in pH, phosphorylation, calcium, and hormones can open or close the channels or alter which molecules are transported, linking aquaporin activity tightly to the cell's environment.

FROM WATER CHANNELS TO CANCER DRIVERS

Over the last decade, the role of aquaporins in cancer biology has attracted intense interest. Studies in breast tissue have shown that many aquaporins are expressed both in normal mammary glands and in breast tumors, often with strikingly different patterns between healthy and malignant tissue. In normal adipose tissue, aquaglyceroporins such as AQP7 regulate glycerol flux, thereby influencing triglyceride storage, lipolysis, and overall energy balance. Dysregulation of these glycerol channels has been linked to obesity, insulin resistance, and altered lipid metabolism—conditions that themselves intersect with breast cancer risk and progression.

In breast cancer, specific aquaporin isoforms are associated with fundamental hallmarks of malignancy: uncontrolled proliferation, enhanced migration and invasion, angiogenesis, and metastatic spread. Expression analyses suggest that some aquaporins are upregulated (for example, AQP1, AQP8, AQP9 or AQP10 in certain datasets), while others such as AQP3, AQP4, AQP5, and AQP7 may be downregulated or mislocalized depending on tumor subtype and context. Importantly, protein localisation—where in the cell or tissue an aquaporin is expressed—often provides more prognostic information than mRNA levels alone.

ISOFORM-SPECIFIC ROLES IN BREAST CANCER

Although the aquaporin family is structurally related, individual members appear to have distinct roles in breast cancer biology.

Aquaporin-1 (AQP1)

AQP1 is typically found in endothelial cells and is strongly involved in angiogenesis. In breast tumours, higher AQP1 expression has been linked to increased microvessel density, more aggressive growth, and enhanced migration and invasion of cancer cells. In experimental models, depletion of AQP1 leads to abnormal tumor microvasculature and impaired tumour expansion.

Aquaporin-3 (AQP3)

AQP3 is an aquaglyceroporin expressed in many epithelial tissues, including mammary glands, where it supports glycerol transport and cellular hydration. In breast cancer cell lines such as MCF-7 and T47D, AQP3 promotes cell migration and invasion and regulates epithelial–mesenchymal transition (EMT)–related genes and cytoskeletal organisation. High AQP3 expression in estrogen receptor–positive tumors has been associated with poor differentiation and increased lymph node metastasis.

Aquaporin-4 (AQP4)

Better known for its role in the brain, AQP4 is also expressed in breast tissue. Silencing AQP4 in breast cancer cells reduces proliferation, migration, and invasion, while increasing E-cadherin expression, suggesting that AQP4 influences cell–cell adhesion and may modulate EMT and tissue architecture.

Aquaporin-5 (AQP5)

AQP5 has emerged as a prognostic marker in several cancers, including breast cancer. Its expression correlates with altered signaling through pathways such as Ras and Rac1 and with disruptions in epithelial cell–cell adhesion. Experimental knockdown of AQP5 reduces cell migration and proliferation, while overexpression in fibroblasts enhances their motility and can drive tumor formation, partly through activation of ERK signalling.

Aquaporin-7 (AQP7)

As a key glycerol channel in adipocytes, AQP7 links metabolism to cancer. In breast tumors, high AQP7 protein expression has been associated with poorer overall survival, and functional studies suggest that AQP7 promotes cell proliferation, modulates adhesion, and affects contact inhibition. Knockdown of

AQP7 reduces primary tumor burden and metastatic potential in experimental models, supporting its role as a negative prognostic marker.

Taken together, these findings position aquaporins not as passive channels but as active regulators of breast cancer behaviour, often integrating metabolic, structural, and signalling cues.

AQUAPORIN AND THE TUMOR MICROENVIRONMENT

Breast cancer does not develop in isolation; it arises within a complex tumor microenvironment composed of stromal fibroblasts, adipocytes, immune cells, extracellular matrix, and an often-abnormal vasculature. Aquaporins contribute to this microenvironment on several levels.

In fibroblasts, for example, overexpression of AQP5 increases motility and proliferation and supports tumor formation when these cells interact with cancer cells. This effect is coupled to activation of ERK1/2 signalling, illustrating how a water channel can modulate intracellular signalling cascades. Conversely, specific mutations in AQP5 can prevent tumor formation, highlighting the importance of precise structural features.

Mesenchymal stem cells within the tumor niche can promote breast cancer growth and angiogenesis by secreting cytokines and growth factors. Aquaporins expressed by both stromal and cancer cells likely help these cells adapt to hypoxic, nutrient-poor regions by facilitating water and solute flux, volume regulation, and possibly gas transport through central pores. Hypoxia and abnormal vascularisation—common features of solid tumors—can in turn modify aquaporin expression, creating feedback loops that support tumor survival and therapy resistance.

AQUAPORINS AS BIOMARKERS AND THERAPEUTIC TARGETS

Aquaporins' cell-type-specific expression and strong prognostic associations make them compelling candidates as both biomarkers and therapeutic targets in breast cancer. Distinct AQP expression profiles correlate with tumor subtype, grade, relapse-free survival and overall survival, and isoforms like AQP1 and AQP7 have been linked—depending on context—to either favourable or poor outcomes, supporting the idea of a multi-marker aquaporin panel to refine risk stratification and guide treatment choices.

Therapeutically, aquaporins can modulate chemosensitivity: for example, higher AQP1 expression in invasive ductal carcinoma has been associated with better response to anthracycline-based regimens, while experimental inhibition of AQP5 in colorectal cancer reduces proliferation and increases apoptosis, suggesting that similar approaches might benefit breast cancer. Despite this promise, translating aquaporin biology into drugs is difficult because existing inhibitors are often poorly selective, hit multiple isoforms, and show significant off-target effects, making improved potency, selectivity and solubility urgent goals. A rational path forward is to test refined aquaporin inhibitors first as monotherapies in preclinical breast cancer models and then in combination with chemotherapy, endocrine therapy or targeted agents.

Overall, aquaporins have evolved from simple water channels to complex regulators at the intersection of membrane transport, metabolism, signalling, and tumor microenvironment interactions.

CONCLUSION

Aquaporins now stand out as promising, but still under-utilised, biomarkers and therapeutic targets in breast cancer, with isoform-specific expression patterns that can inform prognosis and treatment response. Going forward, mastology research should focus on validating aquaporin panels for early diagnosis and risk stratification, dissecting stromal versus tumor-cell contributions in different molecular subtypes, and designing highly selective aquaporin inhibitors that can be safely combined with standard systemic therapies.

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www.journalworlds.com
AGRI JOURNAL WORLD
VOL. 6 ISSUE 2 APRIL-JUNE, 2026

NANOBIOCHAR: A NEXT-GENERATION SOIL AMENDMENT FOR SUSTAINABLE AGRICULTURE

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ABSTRACT

Agriculture today faces a complex set of challenges, including declining soil fertility, nutrient losses, water scarcity, and contamination from heavy metals and agrochemicals. Farmers and researchers are therefore exploring innovative materials that can improve soil health while supporting sustainable crop production. One such emerging material is nanobiochar, a nanoscale form of biochar with enhanced physicochemical properties and wide agricultural potential. Derived from biomass and engineered into extremely fine particles, nanobiochar is gaining attention as a multifunctional amendment capable of improving nutrient use efficiency, soil structure, water retention, and environmental quality.

KEYWORDS: Biochar, Nanobiochar, Soil health, Sustainable Agriculture

WHAT IS NANOBIOCHAR?

Biochar is a carbon-rich material produced by heating biomass such as crop residues, wood chips, manure, or other organic wastes under limited oxygen conditions, typically at temperatures ranging from about 300 to 700°C. When this biochar is further processed into particles ranging roughly between 1 and 100 nanometers, it is referred to as nanobiochar. The drastic reduction in particle size transforms ordinary biochar into a highly reactive material with unique characteristics.

Compared with conventional biochar, nanobiochar possesses a much larger specific surface area, smaller particle size, higher reactivity, and a greater abundance of oxygen-containing functional groups. These properties enable nanobiochar to interact more efficiently with soil particles, nutrients, and microorganisms. In addition, nanobiochar typically exhibits a negative surface charge, which improves its ability to retain positively charged nutrients such as ammonium, potassium, calcium, and micronutrients. Because of these advantages, nanobiochar is increasingly being considered a next-generation soil amendment with applications in crop production, soil remediation, and climate-smart agriculture.

PREPARATION OF NANOBIOCHAR

The production of nanobiochar generally involves two main steps. First, biomass is converted into bulk biochar through thermochemical processes such as pyrolysis. Second, the bulk biochar is further processed to reduce particle size to the nanoscale. Several methods are used for this size reduction (Chausali et al., 2021).

1. BALL MILLING METHOD

Ball milling is one of the most widely used techniques for producing nanobiochar. In this process, bulk biochar is placed in a milling chamber containing hardened balls that rotate at high speed. The mechanical impact and friction break down larger particles into nanosized fragments. During milling, longitudinal pores and channels are compressed, creating new micro- and nano-pores (Ramanayaka et al., 2020). This results in increased surface area and improved adsorption capacity. Ball milling can be performed in dry or wet conditions. In dry milling, biochar is ground without any liquid medium, whereas in wet milling, water or another solvent is added. This method is considered environmentally friendly, relatively low-cost, and reproducible, making it suitable for large-scale preparation.

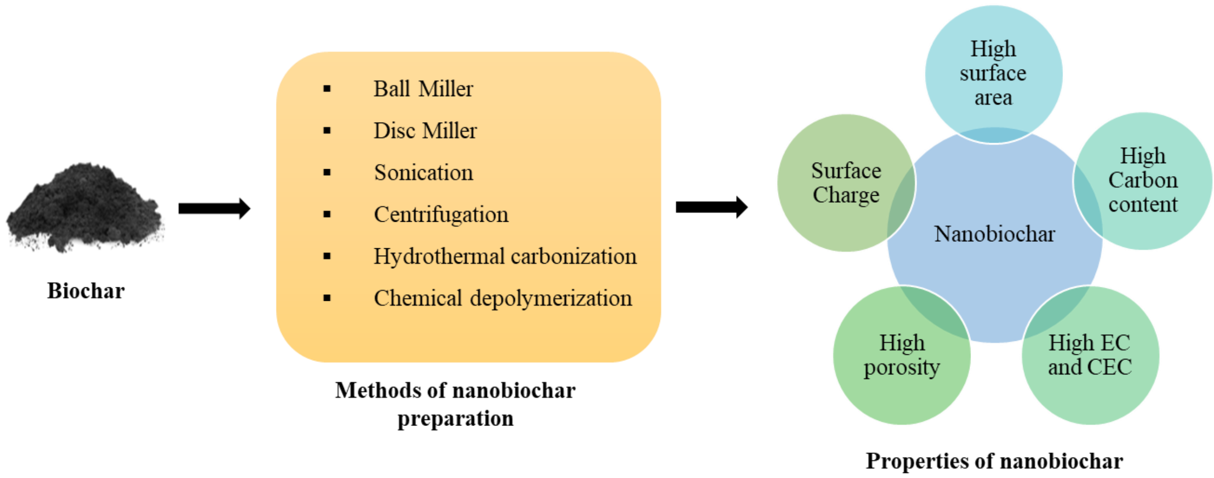

Fig 1. Methods of preparation and properties of nanobiochar

2. ULTRASONICATION METHOD

Ultrasonication involves dispersing biochar in a liquid medium and exposing it to high-frequency ultrasound waves. These waves generate microbubbles that collapse violently, producing shockwaves and microjets. The resulting forces break apart biochar particles and exfoliate graphite-like structures within the material. This process opens blocked pores, creates new micropores, and enhances surface reactivity. Ultrasonication is efficient because it often requires only one step and minimal chemical inputs. The resulting nanobiochar typically exhibits improved dispersion and higher adsorption capacity.

3. CENTRIFUGATION AND OTHER APPROACHES

Centrifugation is often used after milling or ultrasonication to separate nanosized particles from larger fractions. Other emerging approaches include microwave-assisted methods and chemical modifications, which further tailor nanobiochar properties for specific agricultural applications.

KEY PROPERTIES OF NANOBIOCHAR

Nanobiochar exhibits distinctive physicochemical properties that make it particularly useful in agricultural systems (Pathak et al., 2024).

- *HIGH SURFACE AREA AND POROSITY:* Nanobiochar contains abundant nano-pores that greatly increase its surface area. This large surface provides numerous sites for adsorption of nutrients, water, and pollutants. Higher pyrolysis temperatures often enhance pore development, further improving adsorption capacity.
- *HIGH ADSORPTION CAPACITY:* The porous structure and active functional groups allow nanobiochar to efficiently adsorb nutrients, heavy metals, and organic contaminants. This property makes it suitable for slow nutrient release and immobilization of toxic elements in soil.
- *IMPROVED WATER-HOLDING CAPACITY:* Nanobiochar can retain water within its pore network, enhancing soil moisture availability. This feature is especially beneficial under drought or rainfed conditions, where maintaining soil moisture is critical for crop growth.
- *ABUNDANT FUNCTIONAL GROUPS:* The surface of nanobiochar contains oxygen-containing functional groups such as carboxyl (–COOH), hydroxyl (–OH), and carbonyl (C=O). These groups improve nutrient retention, increase cation exchange capacity, and support microbial colonization.
- *ALKALINE NATURE:* Most nanobiochar materials are neutral to alkaline, which helps reduce soil acidity. This can improve nutrient availability and create a more favorable environment for plant growth.
- *HIGH CARBON CONTENT AND STABILITY:* Nanobiochar is rich in stable aromatic carbon structures. This contributes to long-term carbon sequestration, improved soil aggregation, and enhanced soil structure.

- *NEGATIVE SURFACE CHARGE:* Nanobiochar typically carries a negative surface charge, improving its ability to adsorb positively charged nutrients and metals. This also enhances colloidal stability and dispersion in soil.
- *SMALL PARTICLE SIZE AND HIGH REACTIVITY:* Because of its nanoscale size, nanobiochar can interact closely with plant roots and soil microorganisms. This increases nutrient exchange and improves soil biological activity.

APPLICATIONS OF NANOBIOCHAR IN AGRICULTURE

1. *NUTRIENT RETENTION AND SLOW RELEASE:* One of the major limitations of conventional fertilizers is nutrient loss through leaching, volatilization, and runoff. Nanobiochar can adsorb nutrients and release them gradually, improving nutrient use efficiency. When applied with fertilizers, nanobiochar acts as a carrier that reduces nutrient losses and enhances availability to plants.
2. *SOIL STRUCTURE IMPROVEMENT:* Nanobiochar enhances soil aggregation by binding soil particles together. Improved aggregation leads to better aeration, root penetration, and water infiltration. Over time, this improves soil fertility and productivity.
3. *ENHANCEMENT OF MICROBIAL ACTIVITY:* The porous structure of nanobiochar provides a habitat for beneficial soil microorganisms. These microbes play a vital role in nutrient cycling, organic matter decomposition, and plant growth promotion. Increased microbial activity also contributes to improved soil health.
4. *WATER CONSERVATION:* Nanobiochar improves soil water retention by storing moisture in its pores. This helps crops withstand short dry spells and reduces irrigation requirements. In sandy soils, nanobiochar significantly enhances water-holding capacity.
5. *HEAVY METAL IMMOBILIZATION:* Nanobiochar has strong adsorption capacity for heavy metals such as cadmium, lead, and copper (Jiang et al., 2023). By binding these metals, nanobiochar reduces their mobility and bioavailability. This makes it useful for reclaiming contaminated soils and protecting crop safety.
6. *REMOVAL OF ORGANIC POLLUTANTS:* Nanobiochar can adsorb pesticides, herbicides, and other organic pollutants. It reduces their movement in soil and water systems and may even facilitate degradation through catalytic processes. This contributes to cleaner agricultural environments.
7. *CARBON SEQUESTRATION AND CLIMATE MITIGATION:* Because nanobiochar is composed of stable carbon, it helps store carbon in soil for long periods. This reduces atmospheric carbon dioxide and contributes to climate change mitigation. At the same time, improved soil fertility supports

sustainable crop production.

8. *USE IN NANO-FERTILIZER DEVELOPMENT:* Nanobiochar can serve as a carrier material for nano-fertilizers. Nutrients loaded onto nanobiochar particles can be released slowly and efficiently near plant roots. This approach reduces fertilizer requirements and minimizes environmental pollution.

ADVANTAGES OF NANOBIOCHAR IN AGRICULTURE

- Improves nutrient use efficiency
- Enhances soil water retention
- Promotes microbial activity
- Reduces heavy metal toxicity
- Improves soil structure and aggregation
- Acts as a slow-release nutrient carrier
- Supports carbon sequestration
- Reduces environmental pollution

CHALLENGES AND FUTURE PROSPECTS

Despite its promising potential, nanobiochar use in agriculture is still emerging. Large-scale production methods need optimization to ensure cost-effectiveness. There is also a need to evaluate long-term effects on soil ecosystems and crop productivity. Standardized guidelines for safe application rates are required, particularly because nanoscale materials may behave differently from conventional amendments (Bhandari et al., 2023).

Future research is focusing on combining nanobiochar with fertilizers, microbial inoculants, and organic amendments. Such integrated approaches may enhance sustainability and improve crop yields while reducing environmental risks.

CONCLUSION

Nanobiochar represents a promising innovation for sustainable agriculture. Its nanoscale size, large surface area, and high reactivity make it more effective than conventional biochar in improving soil fertility, nutrient retention, water availability, and pollutant immobilization. By enhancing soil health and reducing nutrient losses, nanobiochar can contribute to improved crop productivity and environmental protection. With continued research and careful field evaluation, nanobiochar has the potential to become an important component of climate-smart and resource-efficient farming systems.

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AGRI JOURNAL WORLD
VOL. 6 ISSUE 2 APRIL-JUNE, 2026

PROTEIN YIELD GAP IN PULSES: WHY INDIA GROWS LEGUMES BUT STILL FACES PROTEIN DEFICIENCY

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ABSTRACT

India is the world's largest producer of pulses, yet protein deficiency remains widespread, highlighting a significant protein yield gap. This gap extends beyond grain production to include protein quality, digestibility, post-harvest losses, affordability, consumption patterns, and inefficiencies in the pulse value chain. Biological, agronomic, socioeconomic, and policy factors further influence this challenge. This article explores the multiple dimensions of the protein yield gap in Indian pulses and discusses integrated strategies to enhance pulse production, nutritional quality, accessibility, and consumption for improved food and nutrition security.

KEYWORDS: Anti-nutritional factors, DIAAS, Legumes, Protein deficiency, Protein quality, Protein yield gap, Pulses

INTRODUCTION

India occupies a unique and paradoxical position in global protein nutrition. On one hand, it is the world's largest producer of pulses, growing chickpea (*Cicer arietinum*), pigeon pea (*Cajanus cajan*), lentil (*Lens culinaris*), black gram (*Vigna mungo*), and green gram (*Vigna radiata*) across approximately 29-30 million hectares and producing over 24 million tonnes annually (Agriculture.Institute, 2026). On the other hand, it is home to one of the largest protein-deficient populations in the world, with estimates suggesting that over 70% of Indians do not meet their daily protein requirements (ORF, 2021).

A recent analysis by the Council on Energy, Environment and Water (CEEW, 2025) found that while Indians consume an average of 55.6 g of protein per day, nearly 50% of this protein comes from cereals such as rice and wheat - foods with an inherently poor amino acid profile - while pulses, dairy, and eggs remain significantly under-consumed. The richest 10% of the Indian population consumes 1.5 times more protein than the poorest, revealing a deep inequality in protein access (CEEW, 2025).

Understanding why this production-nutrition paradox persists demands a multi-dimensional analysis of the protein yield gap - defined here not just as the difference between potential and actual pulse yields, but as the full gap between what India's pulse sector could deliver in terms of digestible, high-quality protein per person and what it actually does deliver.

UNDERSTANDING THE PROTEIN YIELD GAP IN PULSES

The protein yield gap in pulses operates on two distinct levels that must be addressed simultaneously:

- Quantity gap: The difference between potential pulse grain yield per hectare (under optimal management) and actual farm-level yield. India's pulse productivity stands at only 889 kg/ha, well below the global average of 964 kg/ha (Agriculture.Institute, 2026).
- Quality gap: Even when pulses are produced, the digestible protein available for human absorption is reduced by anti-nutritional factors, poor amino acid profiles (particularly deficiency of sulfur amino acids methionine and cysteine), and processing-related protein losses.

Table 1: Protein Yield Gap Analysis of Major Indian Pulse Crops

Pulse Crop	Potential Protein Yield (kg/ha)	Actual Protein Yield (kg/ha)	Yield Gap (%)	Limiting Amino Acid	DIAAS Score
Chickpea	420-480	180-230	~55%	Methionine + Cysteine	0.56-0.68
Pigeon Pea	380-440	160-200	~58%	Methionine + Cysteine	0.52-0.65
Lentil	400-460	185-220	~53%	Methionine + Cysteine	0.58-0.72
Black Gram	360-420	155-195	~57%	Methionine + Tryptophan	0.50-0.63
Green Gram	350-400	160-190	~54%	Methionine + Cysteine	0.53-0.67

Source: Compiled from ICRISAT, FAO, and Herreman et al. (2020) data

The protein quality of pulses, when assessed by the Digestible Indispensable Amino Acid Score (DIAAS) - the internationally recommended method - ranges from 0.47 to 0.75, well below scores of 1.0 or higher seen in animal-based proteins (Herreman et al., 2020). This means that even when pulses are consumed, their usable protein content is substantially lower than crude protein figures suggest.

KEY DRIVERS OF THE PROTEIN YIELD GAP

1. *AGRONOMIC YIELD GAP: RAINFED CONDITIONS AND LOW INPUTS:* About 85-90% of pulse cultivation in India occurs under rainfed conditions, making these crops highly vulnerable to rainfall variability, drought stress, and waterlogging (Lybbert et al., 2024). Unlike rice and wheat, which receive the majority of irrigation, fertilizer subsidies, and institutional support, pulses are predominantly grown on marginal soils with minimal external inputs. This results in a massive agronomic yield gap - the difference between what pulse crops could yield under best management practices and what farmers actually achieve.
2. *PROTEIN QUALITY GAP: ANTI-NUTRITIONAL FACTORS:* Raw pulses contain a range of anti-nutritional factors (ANFs) including phytic acid, tannins, trypsin inhibitors, haemagglutinins (lectins), and oxalates that significantly reduce protein digestibility and mineral bioavailability (Samtiya et al., 2020). Phytic acid alone can reduce iron absorption by 50-80% and zinc absorption by 15-35%. While traditional cooking methods (boiling, soaking, fermenting, and sprouting) can reduce ANF content by 50-90%, inadequate processing, especially among rural and low-income households, means that the full protein value of pulses is rarely realized.
3. *STRUCTURAL INEQUALITY: PRICE, ACCESS, AND AFFORDABILITY:* Pulses have historically been among the most price-volatile food commodities in India, with retail prices of arhar (pigeon pea) dal frequently exceeding ₹150-200 per kg during periods of production shortfall. This price volatility effectively prices out the most protein-deficient segments of the population - the poor - from adequate pulse consumption. Lybbert et al. (2024) demonstrated that domestic pulse production in India has consistently lagged behind demand growth since 1995, with consumption growing at 2.3% annually against production growth of only 1%, forcing heavy reliance on imports.
4. *CONSUMPTION PATTERNS AND AWARENESS GAP:* The CEEW (2025) analysis, based on the 2023-24 NSSO Household Consumption Expenditure Survey, revealed that while average protein intake figures appear adequate at 55.6 g/day, the quality and diversity of protein sources are deeply inadequate. Cereals supply nearly 50% of protein intake - far above the National Institute of Nutrition's recommended 32% - crowding out high-quality protein sources like pulses. The "Protein

Paradox” study further identified three key barriers: paucity of knowledge, psychological misconceptions, and pinch of affordability (ORF, 2021).

5. *POST-HARVEST LOSSES:* Post-harvest losses in the Indian pulse value chain are estimated at 8-12% of total production, primarily due to inadequate storage infrastructure, insect pest infestation (pulse beetle, *Callosobruchus maculatus*), and moisture-related deterioration. Beyond quantitative losses, storage damage also degrades protein quality through denaturation, Maillard browning reactions, and amino acid cross-linking, further widening the effective protein yield gap.

Table 2: Dimensions of the Protein Yield Gap in Indian Pulses and Corresponding Interventions

Dimension of Gap	Key Cause	Scale of Impact	Recommended Intervention
Agronomic yield gap	Rainfed conditions, poor inputs	High (889 vs 964 kg/ha)	Irrigation, HYV seeds, fertilization
Protein quality gap	Anti-nutritional factors	Moderate-High (reduces DIAAS by 25-40%)	Processing, biofortification, variety selection
Digestibility gap	Limiting amino acids (Met, Cys)	Moderate (DIAAS 0.5-0.75)	Complementary feeding: pulse + cereal
Access and affordability gap	Price volatility, low farm profitability	High among poor households	MSP support, buffer stocks, PDS inclusion
Awareness gap	Low protein literacy	Population-wide	Nutrition education, campaigns
Post-harvest loss gap	Storage, pest, and moisture losses	8-12% of production	Hermetic storage, cold chains, processing hubs

BRIDGING THE PROTEIN YIELD GAP: AN INTEGRATED APPROACH

- *CLOSING THE AGRONOMIC GAP: TECHNOLOGY AND POLICY:* India’s National Food Security

- Mission (NFSM)-Pulses has made significant strides in expanding pulse cultivation, with production growing from 16.3 million tonnes in 2015-16 to 24.5 million tonnes in 2023-24 through area expansion and improved variety adoption (Agriculture Institute, 2026). Scaling up micro-irrigation in pulse-growing zones, expanding distribution of climate-resilient short-duration varieties, and ensuring stable Minimum Support Price (MSP) procurement are essential to sustain this momentum and narrow the agronomic yield gap.
- *IMPROVING PROTEIN QUALITY: PROCESSING AND BIOFORTIFICATION:* Traditional and innovative processing methods can dramatically improve the nutritive value of pulses. Germination (sprouting) increases lysine and reduces phytic acid; fermentation improves digestibility by 20-30%; and roasting reduces trypsin inhibitors. Samtiya et al. (2020) comprehensively reviewed how these simple processing techniques can raise the effective protein quality of pulses to levels competitive with many animal-based sources. Simultaneously, breeding programs at ICRISAT and IARI are developing pulse varieties with higher methionine content and reduced ANF levels, directly addressing the amino acid quality gap.
- *DIETARY COMPLEMENTARITY: PULSES + CEREALS:* A powerful and culturally aligned strategy is the promotion of pulse-cereal complementarity. When pulses (rich in lysine but low in methionine) are consumed together with cereals (rich in methionine but low in lysine), the combined DIAAS of the meal increases significantly. Han et al. (2021) demonstrated that pulse-cereal blends can achieve DIAAS values of 0.85-0.95, approaching the protein quality of animal-based foods. India's traditional diet of dal-roti and dal-chawal intuitively embodies this complementarity principle - the challenge is ensuring adequate pulse quantities in these combinations.
- *POLICY REFORMS: PDS AND NUTRITION LABELLING:* Including pulses in the Public Distribution System (PDS) at subsidized rates for Below Poverty Line (BPL) households is one of the most direct policy levers available to bridge the access gap. Several state governments have already piloted this, with positive outcomes for household protein intake. Simultaneously, mandatory protein quality labelling (displaying DIAAS or PDCAAS scores on packaged dal) would empower consumers to make informed dietary choices - a step aligned with India's evolving food labelling regulations.

CONCLUSION

India's protein paradox - being the world's largest pulse producer while hosting one of the largest protein-deficient populations - is not an accident of fate but the cumulative outcome of agronomic underperformance, protein quality reduction, structural inequalities in access, and insufficient policy integration of nutrition goals into agriculture. The protein yield gap in pulses is therefore not one gap but many - an agronomic gap, a quality gap, an access gap, an awareness gap, and a policy gap. Closing it requires an equally multi-dimensional strategy: expanding irrigated pulse cultivation, deploying biofortified and high-protein varieties, scaling up processing technologies that reduce ANFs, leveraging the power of pulse-cereal dietary complementarity, and integrating pulses into public food safety nets. India has both the agronomic capacity and the traditional food wisdom to solve its protein paradox. What is needed is the political commitment and institutional coordination to transform pulse production into genuine protein security - not just for production statistics, but for every plate across the nation.

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How to cite:

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www.journalworlds.com
AGRI JOURNAL WORLD
VOL. 6 ISSUE 2 APRIL-JUNE, 2026

HARNESSING HYPERACCUMULATOR PLANTS FOR SUSTAINABLE CRITICAL MINERAL RECOVERY

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ABSTRACT

India's growing demand for critical minerals to support renewable energy, electric mobility, and advanced technologies has intensified concerns over import dependence. Phytomining, which uses hyperaccumulator plants to recover valuable metals from low-grade ores, mine wastes, and industrial residues, offers a sustainable alternative. Advances in plant biotechnology and metal recovery have expanded its potential beyond environmental remediation. In India, phytomining can complement conventional mining, restore degraded lands, enhance carbon sequestration, support rural livelihoods, and strengthen critical mineral security, contributing to a circular economy and the vision of Viksit Bharat 2047.

KEYWORDS: Circular economy, critical mineral recovery, ecological restoration, hyperaccumulator plants, phytomining

INTRODUCTION

As India advances its ambitions to become a global leader in electric mobility, renewable energy, advanced manufacturing, semiconductor production, and strategic defence technologies, ensuring a secure and sustainable supply of critical minerals has emerged as a strategic national priority. Minerals such as lithium, nickel, cobalt, vanadium, graphite, scandium, and rare earth elements are indispensable for the production of batteries, solar photovoltaic systems, wind turbines, electronic devices, and advanced defence technologies (Kumar and Bhattacharyya, 2025). However, India's continued reliance on imports for many of these resources exposes the country to supply-chain vulnerabilities, market uncertainties, and geopolitical risks, highlighting the need to diversify and strengthen domestic sources of critical minerals (Government of India, 2025; Kumar and Bhattacharyya, 2025).

In response to these challenges, researchers are increasingly exploring innovative and environmentally sustainable approaches to mineral resource recovery. Among the most promising is phytomining, a nature-based mining strategy that utilizes hyperaccumulator plants to extract and concentrate valuable metals from soils, mine wastes, and other mineral-rich substrates (Rylott and van der Ent, 2025; He et al., 2026). This emerging technology has attracted growing international interest owing to its potential to simultaneously recover critical minerals and restore degraded landscapes. Scientists suggest that India's extensive areas of mine spoils, degraded lands, industrial wastes, fly ash deposits, red mud repositories, and low-grade mineralized resources could serve as untapped reservoirs of critical minerals, accessible through biological harvesting and recovery systems (Akinbile and Mbohwa, 2025).

MINING METALS THROUGH AGRICULTURE

Unlike conventional mining, which depends on energy-intensive processes such as blasting, excavation, crushing, and chemical extraction, phytomining ((Fig 1) harnesses the natural ability of certain plants, known as hyperaccumulators, to absorb and concentrate metals from soils and mineral-rich substrates (He et al., 2026). These extraordinary plants take up unusually high concentrations of metals through their root systems and store them in their shoots, leaves, and stems (Rylott and van der Ent, 2025). Following harvest, the metal-rich biomass can be processed using metallurgical techniques to recover the accumulated metals (Pereira, 2026). To date, more than 750 hyperaccumulator species have been identified worldwide, demonstrating the remarkable diversity of plants capable of concentrating metals at exceptional levels. Studies have successfully recovered nickel, cobalt, thallium, selenium, gold, and rare earth elements from contaminated soils, mine wastes, and low-grade mineral deposits using these species (Rylott and van der Ent, 2025; Akinbile and Mbohwa, 2025). Notably, commercial-scale nickel phytomining has already been established in several regions, providing compelling evidence that plants can serve as effective biological mining tools (Rylott and van der Ent, 2025). More recently, researchers have reported that certain grasses and ferns can accumulate rare earth elements at economically significant concentrations, creating new opportunities for the sustainable recovery of strategic minerals essential for clean-energy and advanced technology applications (Richardson et al., 2025).

A STRATEGIC OPPORTUNITY FOR INDIA

India's heavy reliance on imports of lithium, cobalt, nickel, and several rare earth elements has emerged as a significant strategic and policy concern (Government of India, 2025). In response, the Government of India launched the National Critical Mineral Mission (NCMM), with an allocation of ₹16,300 crore to strengthen domestic capabilities in mineral exploration, mining, processing, recycling, and resource recovery (Government of India, 2025). The mission seeks to build resilient supply chains and enhance the country's long-term critical mineral security. Within this framework, phytomining is increasingly being recognized as a promising complementary approach to conventional mining (He et al., 2026). India possesses extensive areas of abandoned mines, coal overburden dumps, chromite mine wastes, graphite-bearing formations, and industrial waste repositories that remain largely underutilized. Although these sites often contain metal concentrations too low for economically viable conventional extraction, they may offer significant opportunities for recovery through phytomining (Akinbile and Mbohwa, 2025).

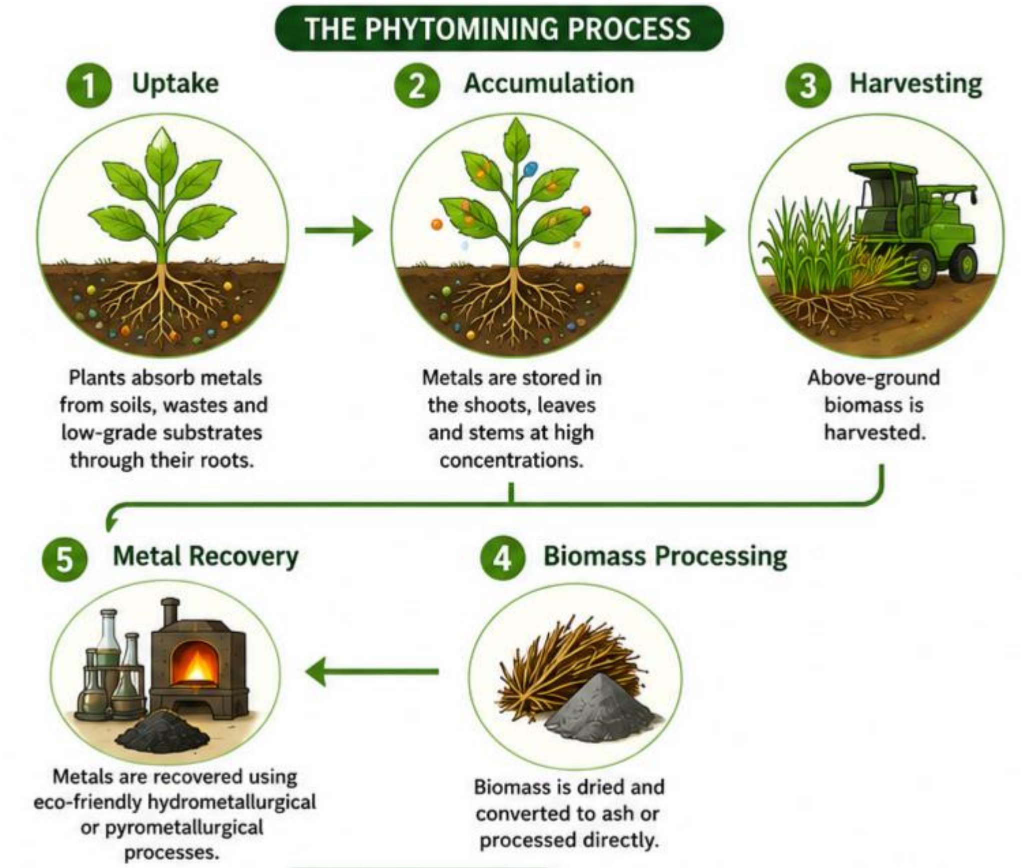

Figure 1. Conceptual framework of phytomining using hyperaccumulator plants for sustainable critical mineral recovery

Reflecting the growing scientific interest in this emerging field, researchers aimed at evaluating the potential of hyperaccumulator plants for the sustainable recovery of critical minerals from mineralised rocks, mine wastes, and degraded landscapes. Particular attention is being directed toward mineral rich states such as Odisha, Jharkhand, Chhattisgarh, Karnataka, Rajasthan, and Arunachal Pradesh, where phytomining could simultaneously contribute to critical mineral recovery and ecological restoration. By harnessing hyperaccumulator plants, these landscapes may become sources of nickel, cobalt, vanadium, and rare earth elements while supporting the rehabilitation of degraded ecosystems (Rylott and van der Ent, 2025; He et al., 2026).

TURNING WASTELANDS INTO "GREEN MINES"

One of the most compelling features of phytomining is its potential to convert environmental liabilities into valuable economic resources (Akinbile and Mbohwa, 2025). Mining operations frequently leave behind degraded landscapes characterized by soil erosion, contamination, biodiversity loss, and reduced land productivity. Conventional rehabilitation measures are often costly and provide limited economic returns. In contrast, hyperaccumulator plants offer a multifunctional solution by extracting valuable metals while simultaneously stabilizing soils, enhancing vegetation cover, reducing dust emissions, and promoting carbon sequestration (He et al., 2026; Akinbile and Mbohwa, 2025).

This integrated approach has led researchers to describe phytomining systems as "green mines" living, self-sustaining systems capable of producing strategic minerals while contributing to environmental restoration and ecosystem recovery (Akinbile and Mbohwa, 2025). Beyond mineral recovery, phytomining may also provide an additional source of renewable biomass. Following harvest, the biomass can be utilized for energy production, and the resulting ash, enriched with concentrated metals, can be processed through hydrometallurgical or pyrometallurgical methods to recover valuable elements, thereby enhancing the overall economic viability of the technology (He et al., 2026; Pereira, 2026).

NEW LIVELIHOOD OPPORTUNITIES FOR RURAL INDIA

Beyond its potential for critical mineral recovery, phytomining may create novel livelihood opportunities for rural and tribal communities, particularly in regions characterized by degraded lands and limited agricultural productivity (He et al., 2026). Unlike conventional mining, which typically requires substantial capital investment, intensive infrastructure, and centralized operations, phytomining can be integrated with landscape restoration initiatives and community based natural resource management programs. The cultivation of hyperaccumulator species on marginal, contaminated, or otherwise unproductive lands offers a means of generating economic value from areas unsuitable for conventional food production. By harvesting metal-enriched biomass, local communities could potentially derive additional income streams while contributing to the recovery of strategically important minerals (He et al., 2026). Such systems may be particularly relevant in mining-affected regions, where land degradation often constrains agricultural livelihoods and limits economic opportunities.

Importantly, phytomining aligns with several national priorities, including the promotion of circular economy principles, sustainable rural development, tribal empowerment, ecological restoration, and climate-resilient livelihood strategies. By linking environmental rehabilitation with resource recovery, phytomining offers a multifunctional approach that simultaneously addresses economic, social, and ecological objectives. In areas where conventional agriculture is challenged by poor soil quality, metal contamination, or recurrent climatic stresses, the cultivation of hyperaccumulator plants could provide a viable alternative land-use option and contribute to the diversification of rural economies (He et al., 2026).

INNOVATION AT THE INTERFACE OF AGRICULTURE AND MINING

Phytomining is increasingly being recognized as a multidisciplinary approach that integrates principles of agriculture, biotechnology, ecology, and mineral resource recovery, thereby redefining the conventional boundaries between biological production systems and extractive industries (Pereira, 2026). As global demand for critical minerals continues to rise, researchers are exploring ways to enhance the efficiency and scalability of phytomining through advances in plant science and environmental biotechnology.

Recent developments in plant breeding, rhizosphere engineering, microbial inoculants, genetic improvement, and soil management have shown considerable potential for increasing both metal accumulation and biomass productivity in hyperaccumulator species (He et al., 2026). These innovations are improving the economic feasibility of phytomining and expanding its applicability to a wider range of mineral resources. In parallel, researchers are investigating engineered and enhanced hyperaccumulator systems capable of recovering a broader spectrum of technology-critical elements, including rare earth elements, lithium, cobalt, nickel, and other battery minerals essential for the clean-energy transition (Rylott and van der Ent, 2025).

Looking ahead, international experts envisage the emergence of dedicated "bio-ore farms" managed production systems specifically designed for the cultivation of metal-accumulating plants and the sustainable recovery of strategic minerals (Rylott and van der Ent, 2025). Such systems could complement conventional mining by providing an environmentally benign and low carbon pathway for resource extraction. Consequently, phytomining is increasingly viewed not as a replacement for traditional mining, but as a complementary technology capable of enhancing resource efficiency, recovering metals from low-grade or secondary resources, and contributing to the development of resilient and sustainable mineral supply chains (Akinbile and Mbohwa, 2025).

A VISION FOR VIKSIT BHARAT 2047

As India advances towards its vision of becoming a developed nation by 2047, ensuring a secure and resilient supply of critical minerals will be as fundamental to national development as energy security and food security (Government of India, 2025). The growing demand for minerals required in renewable energy systems, electric mobility, advanced manufacturing, electronics, and strategic technologies underscores the need for innovative and sustainable approaches to resource security.

In this context, phytomining offers a unique opportunity to simultaneously address multiple national priorities. By harnessing the metal-accumulating capacity of hyperaccumulator plants, phytomining has the potential to contribute to domestic critical mineral production while supporting ecological restoration, reducing import dependence, creating rural livelihood opportunities, and advancing climate and sustainability goals (Rylott and van der Ent, 2025; He et al., 2026). Such multifunctional benefits make phytomining particularly relevant for a country with extensive areas of degraded lands, mine spoils, and industrial waste repositories.

Areas once regarded as unproductive wastelands could potentially be transformed into productive landscapes that generate both ecological and economic value. Strategic investments in research, pilot-scale demonstrations, technology development, and policy support under initiatives such as the National Critical Mineral Mission could help unlock this potential and establish phytomining as a complementary component of India's critical mineral strategy (Government of India, 2025). While conventional mining will continue to play a central role in meeting future mineral demand, phytomining offers an environmentally responsible pathway for recovering metals from low-grade resources, mine wastes, and degraded ecosystems. The mines of the future may therefore extend beyond conventional underground and open-cast operations to include carefully managed landscapes where plants function as biological extractors of strategic minerals. Such systems could contribute to building a more sustainable, resilient, and self-reliant mineral economy in support of the broader vision of Viksit Bharat 2047.

CONCLUSION

Phytomining offers a transformative opportunity to reshape how India secures the critical minerals required for a clean energy and technology-driven future. By harnessing the remarkable metal-accumulating capacity of hyperaccumulator plants, degraded mine lands, industrial waste sites, and other marginal landscapes can be transformed into productive "green mines" that simultaneously recover valuable minerals, restore ecosystems, and create sustainable livelihood opportunities. While phytomining is not a substitute for conventional mining, it provides a complementary, low-carbon, and environmentally responsible approach for recovering strategic minerals from low-grade resources and mine wastes that are often uneconomical to exploit using traditional methods. Realizing this potential will require sustained investments in scientific research, the discovery and domestication of indigenous hyperaccumulator species, pilot-scale demonstrations, advances in biotechnology and metallurgical processing, and enabling policy support under the National Critical Mineral Mission. As India advances towards the vision of Viksit Bharat 2047, integrating agriculture, ecology, and mineral resource management through phytomining can strengthen mineral self-reliance, accelerate ecological restoration, promote circular economy principles, and build a more resilient, sustainable, and resource-secure future.

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How to cite:

Nayak, D. and Gudadhe, N. N. (2026). Harnessing hyperaccumulator plants for sustainable critical mineral recovery. Leaves and Dew Publication, New Delhi 110059. *Agri Journal World* 6 (2): 132-138.

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