SUSTAINABLE FARMING

Bridging Science & Innovation for Agriculture

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FOREWORD

It gives me great pleasure to present the December issue of *Sustainable Farming*, which features a well-selected collection of articles addressing key challenges and emerging trends in agriculture. The coverage of themes such as soil health, climate resilience, digital innovation, and sustainable food systems highlights the interdisciplinary and evolving nature of agricultural science. Contributions on soil carbon management, agroecology, methanotrophs, renewable energy, non-coding RNAs, seedborne mycotoxins, integrated disease management, plant physiology, and visual intelligence for precise plant disease detection together offer a comprehensive perspective on sustainable agricultural development.

Several articles in this issue effectively connect fundamental scientific principles with modern technological applications. The article on plant physiology strengthens understanding of core processes that influence crop growth and productivity, while the article on visual intelligence in plant disease detection demonstrates the growing importance of digital tools in improving crop health management. Such integration of science and technology is essential for enhancing efficiency, resilience, and sustainability in agriculture.

The themes covered align well with national priorities related to sustainable intensification, environmental conservation, and farmer-centric innovation. I am confident that this issue will benefit students, researchers, extension professionals, and farmers. I congratulate the editorial team on their efforts and wish *Sustainable Farming* continued success.

(Pramod Kumar Mishra)

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FOREWORD

I am delighted to note that the December issue of Sustainable Farming, which offers a rich collection of articles addressing vital themes in modern agriculture viz., soil health, climate resilience, digital innovation and sustainable food systems, is ready for publication. The inclusion of topics such as soil carbon management, agroecology, methanotrophs, renewable energy, non-coding RNAs, seedborne mycotoxins, integrated disease management, visual intelligence for precise detection of plant diseases and plant physiology reflects the breadth of contemporary agricultural science.

Particularly noteworthy are the articles "Plant Physiology: Core Processes and Their Applications in Agriculture" and "Visual Intelligence in Precise Detection of Plant Diseases", which together bridge fundamental science with technology-driven solutions. The discussions on digital tools like Plantix and initiatives such as agri-tourism highlight opportunities to enhance productivity and rural livelihoods.

I am confident that this issue will benefit students, researchers, extension professionals, and farmers alike. I congratulate the editorial team and wish Sustainable Farming continued success.

Dhirendra Khare

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FOREWORD

I am pleased to write the foreword for the December issue of Sustainable Farming, which presents a carefully curated collection of articles addressing contemporary challenges and emerging trends in agriculture. The issue highlights important themes, including soil health, climate resilience, digital innovation, and sustainable food systems, reflecting the dynamic, interdisciplinary nature of modern agricultural science.Articles covering soil carbon management, agroecology, methanotrophs, renewable energy, non-coding RNAs, seed-borne mycotoxins, integrated disease management, plant physiology, and visual intelligence for precise plant disease detection collectively provide valuable insights into sustainable agricultural development.

Several contributions in this issue successfully bridge fundamental scientific concepts with advanced technological applications. The article on plant physiology enhances understanding of key processes governing crop growth and productivity, while the article on visual intelligence in plant disease detection underscores the increasing role of digital tools in strengthening crop health management. Such integration of science and technology is vital for improving efficiency, resilience, and sustainability in agriculture.

The themes presented in this issue are well aligned with national priorities on sustainable intensification, environmental conservation, and farmer-centric innovations. I am confident that this issue will serve as a valuable resource for students, researchers, extension professionals, and progressive farmers. I congratulate the editorial team for their dedicated efforts and extend my best wishes to Sustainable Farming for its continued success.

(Vinod Kr Garg)

Editorial

The December 2025 issue of Sustainable Farming presents a timely, well-balanced collection of articles on sustainability, climate resilience, and technological advancement in agriculture. As farming systems face increasing pressure from climate variability, resource limitations, and rising food demand, the need for integrated and science-based solutions has become essential. The articles in this issue collectively emphasise the importance of linking fundamental research with practical, field-oriented applications.

This issue offers a comprehensive perspective by covering soil, plant, microbial, and digital aspects of agriculture. Articles on soil carbon management, agroecology, renewable energy, methanotrophs, and non-coding RNAs highlight emerging scientific approaches to enhance sustainability and mitigate environmental impacts. At the plant level, the article "Plant Physiology: Core Processes and Their Applications in Agriculture" reinforces the role of physiological processes such as photosynthesis, water relations, nutrient uptake, and stress responses in improving crop productivity. Complementing this, the article on "Visual Intelligence in Precise Detection of Plant Diseases in Agriculture" demonstrates the growing role of artificial intelligence and digital tools in early disease detection and crop health management.

In addition, discussions on integrated disease management, seedborne mycotoxins, and digital advisory platforms such as Plantix emphasise the practical relevance of research-driven innovations. Initiatives promoting agri-tourism further reflect opportunities for diversification and strengthening rural livelihoods. Together, the contributions underscore the need to integrate scientific knowledge, technological innovation, and farmer welfare to achieve sustainable agricultural development.

We hope that this issue will serve as a valuable resource for students, researchers, extension professionals, policymakers, and farmers, and contribute meaningfully to advancing resilient and sustainable farming systems.

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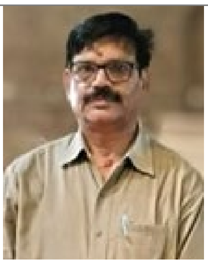

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<u>**Content**</u>

Soil Carbon Dynamics and Sustainable Management: Pathways for Climate Mitigation and Food Security

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Abstract

Soil carbon dynamics plays a pivotal role in maintaining agricultural productivity, ecological stability, and climate regulation. Soil acts as both a reservoir and the source of carbon, with its balance influenced by land use, climate, soil type, and management practices. Sustainable approaches such as conservation tillage, crop rotations, agroforestry, organic amendments, and biochar application improve soil health while enhancing long-term carbon storage. Strengthening the soil carbon sequestration not only mitigates greenhouse gas emissions but also contributes to food security and resilience under a changing climate. Recognising soil as a living resource is essential for designing strategies that ensure a sustainable future.

Introduction

The dynamics of soil carbon are essential to agricultural productivity, ecosystem health, and the regulation of the global climate. By cycling between storage as organic matter and release as carbon dioxide (CO_2) or methane (CH_4) through microbial activity and decomposition, soil serves as both a source and a sink of carbon. While inorganic carbon, mainly in the form of carbonates, is stable primarily, organic carbon, which comes from plant and animal waste, promotes soil fertility and microbial communities. Climate, land use, soil type, and management techniques are some of the variables that affect the carbon balance in soil (Jagadesh et al., 2023). While clay-rich soils are better at holding carbon because they bind organic matter, a warm climate often accelerates organic matter decomposition, releasing CO_2. While conservation techniques such as crop rotation, reduced tillage, and organic amendments improve carbon sequestration, unsustainable agricultural practices like heavy tillage deplete soil carbon reserves. With sustainable land management techniques helping to improve organic carbon storage, soil carbon sequestration has the potential to reduce greenhouse gas emissions on a global scale significantly (Jagadesh et al., 2024a). Cutting-edge techniques such as composting, agroforestry, and biochar use enhance soil structure and carbon retention while promoting biodiversity and food security. To prevent carbon loss and maintain soil health, proactive management is crucial, as soil carbon reserves remain susceptible to climate change. We can tackle the issues of global warming, promote agricultural resilience, and ensure a sustainable future for future generations by acknowledging soil as an essential natural resource and implementing science-based solutions.

The Carbon Cycle and Soil

The soil contributes to the atmospheric CO_2 equilibrium by acting as both a source and a sink of carbon. During photosynthesis, plants absorb CO_2 and store it as organic matter. Some carbon is released back into the atmosphere as CO_2 or CH_4 during the decomposition of plants and other creatures, while the remainder is stored in the soil (Paustian et al., 2019). Whether soil functions as a net carbon sink or source depends on this delicate equilibrium.

Table 1. Soil carbon sequestration practices and their impacts

Sl. No	Practice	Key Findings	Reference
1.	Global Soil Carbon Storage	Total soil carbon and nitrogen stocks vary widely with soil type and climate. Tropical soil is more vulnerable to carbon loses due to rapid turnover.	(Batjes., 1996)
2.	Soil Management for Climate and Food Security	Conservation agriculture practices such as no-till and residue retention increase carbon sequestration and improve food security.	(Lal, 2004)
3.	Managing World Soils for Sustainability	Improved soil management enhances fertility and resilience while mitigating greenhouse gas emissions.	(Lal., 2001)
4.	Controls on Soil Carbon	Long-term experiments demonstrate that management practices such as covering crops and reduced tillage significantly regulate carbon accumulation and release.	(Paustian et al., 2019)

Factors Influencing Soil Carbon Dynamics

A range of interconnected factors influences soil carbon dynamics. Climate plays a decisive role, as temperature and rainfall regulate microbial activity and decomposition rates, often accelerating organic matter breakdown in warmer regions and releasing more carbon dioxide into the atmosphere (Batjes, 1996). Land use changes such as deforestation, urban expansion, and intensive farming significantly alter soil carbon reserves, with practices like frequent tillage exposing organic matter to oxygen and hastening its decomposition (Lal, 2004). Soil type is equally important, since clay-rich soils have a greater capacity to retain carbon due to strong binding with organic matter (Jagadesh et al., 2024b). Equally, sound management practices, including crop rotations, use of cover crops, and reduced tillage, enhance soil carbon storage while maintaining long-term soil health.

Soil Carbon and Climate Change

The importance of soil in reducing climate change has drawn attention from all over the world. Greenhouse gas emissions can be partially mitigated by increasing soil organic carbon stores. Better farming methods can enhance carbon storage worldwide (Lal, 2001). However, when climate conditions change, soil carbon is susceptible to release, highlighting the necessity of sustainable land management.

Promoting Soil Carbon Sequestration

Promoting soil carbon sequestration requires the adoption of sustainable land management practices that strengthen soil health while mitigating climate change. Conservation agriculture, which includes methods such as no-till farming, crop residue retention, and diverse cropping systems, reduces soil disturbance and helps build long-term carbon reserves. Agroforestry further enriches the soil by combining trees with crops and livestock, adding continuous organic inputs and improving ecosystem resilience. The use of biochar, a stable carbon-rich material derived from biomass, enhances soil structure and provides a lasting form of carbon storage. Similarly, organic amendments like compost and manure supply essential nutrients, boost microbial activity, and sustain soil organic matter. Together, these practices create a foundation for productive, resilient, and climate-friendly agriculture. The role of soil carbon sequestration and its impacts are discussed in Table 1.

Conclusion

The dynamics of soil carbon are crucial to international efforts to mitigate climate change and guarantee food security. We can improve soil health, increase carbon sequestration, and lessen the adverse effects of global warming by implementing sustainable soil management techniques. The soil beneath our feet is a treasure of carbon and life, and as stewards of the world, we must acknowledge its vital function.

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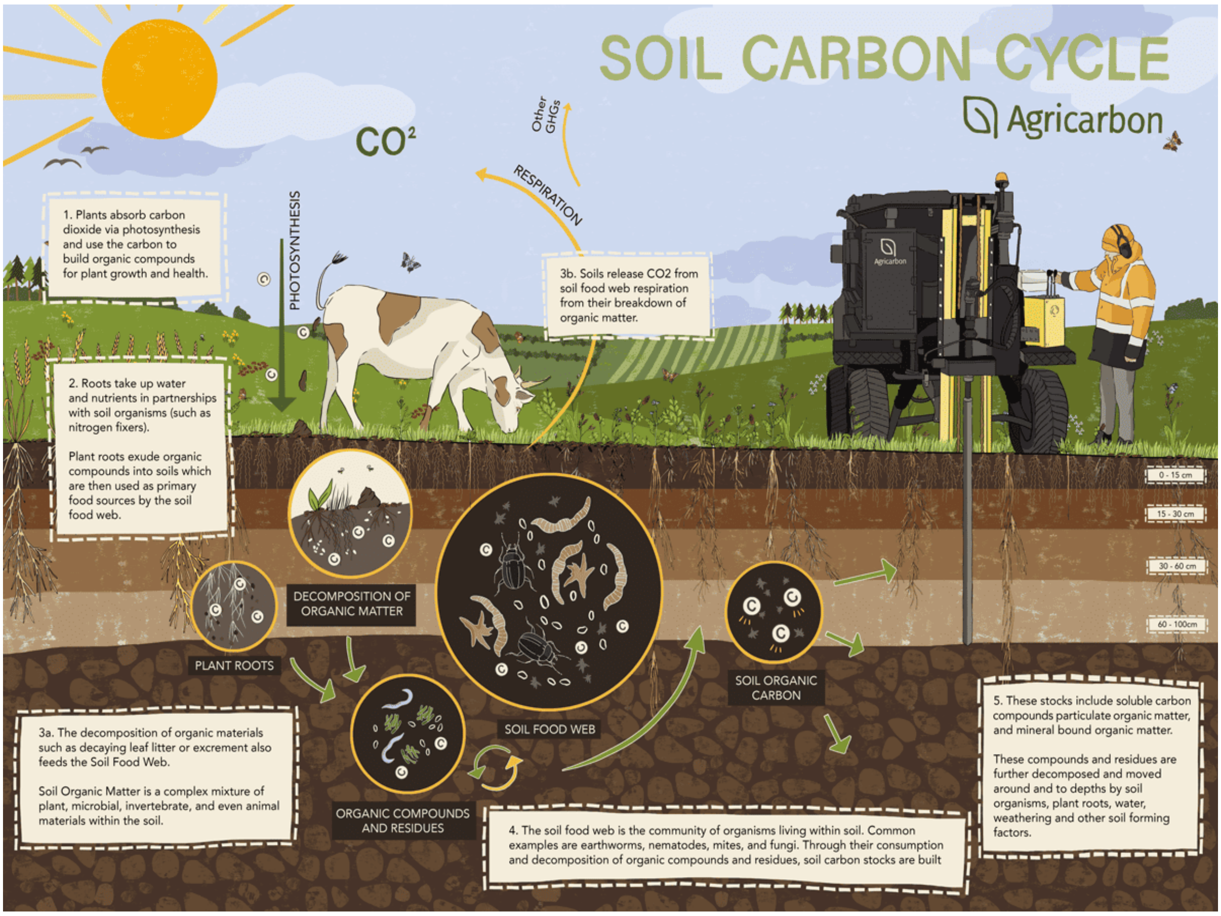

Figure 1: Pathways for Climate Mitigation and Food Security

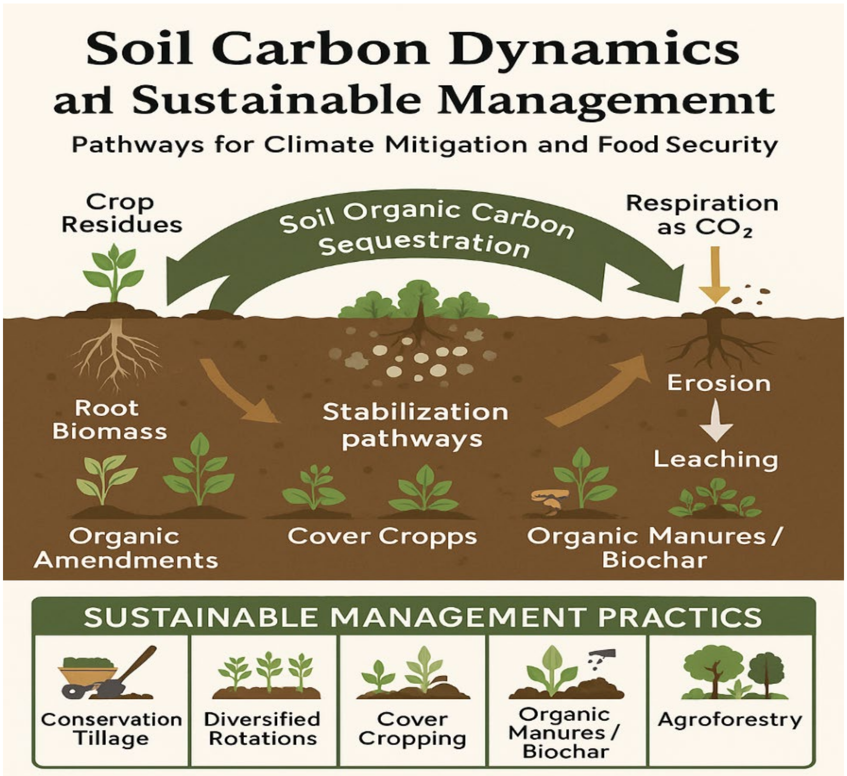

Figure 2: Soil Carbon Dynamics and Sustainable Management for Climate Mitigation and Food Security

Sustainable Diets and Agroecology: Linking Soil Health to Nutritional Well-being

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Abstract
The global food system is undergoing a crucial transformation toward sustainability, with a growing recognition that soil health is fundamental to both agricultural productivity and human nutrition. Agroecology, the integration of ecological principles into food production, offers a holistic approach to ensuring sustainable diets that are both nutritious and environmentally sound. This article examines the role of sustainable soil management and a food secure environment in enhancing dietary quality and community nutrition outcomes.

Introduction

Sustainable agriculture is a farming approach that aims to meet current food needs without compromising the ability of future generations to meet their own. It integrates environmental health, economic profitability and social and economic equity. Sustainable agriculture plays a vital role in enhancing food and nutrition security by promoting diverse cropping systems, organic farming and local food networks. It ensures access to fresh, nutrient-rich produce. Millets, legumes, and indigenous vegetables, often grown sustainably, are rich in fibre, protein, and micronutrients, supporting balanced diets and reducing malnutrition. Minimising chemical inputs preserves soil health and reduces toxic residues in food. Sustainable practices also encourage seasonal eating and reduce food miles, lowering environmental impact. When communities embrace agroecological methods, they not only protect ecosystems but also foster healthier eating habits. Thus, sustainable agriculture is a cornerstone for nourishing populations while safeguarding planetary health and cultural food traditions.

According to FAO (2025), Sustainable Food and Agriculture (SFA) contributes to all four pillars of food security, that is, availability, access, utilisation and stability, with the dimensions of sustainability (environmental, social and economic). FAO promotes SFA to help countries worldwide achieve Zero Hunger and the Sustainable Development Goals. FAO ensures that, over the past decade, an increasing number of countries have begun to incorporate sustainability considerations into their food policies and consumer education programmes. According to the FCRN (Food Climate Research Network), a sustainable diet is one that has low environmental impacts, contributing to food and nutrition security and a healthy life for present and future generations. These types of diets are protective and respectful of biodiversity and ecosystems, culturally acceptable, accessible, economically fair and affordable;

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nutritionally adequate, safe and healthy, while optimising natural and human resources.

Thus, a sustainable diet is one that:

- Promotes a plant-based diet primarily
- Focus on seasonal and local foods
- Reduction of food waste
- Consumption of fish from sustainable stocks only
- Reduction of red and processed meat, highly processed foods and sugar-sweetened beverages

A sustainable diet directly addresses nutrition by promoting dietary diversity and food quality. The relationship between soil health and human health is fundamental and cyclical; healthy soil produces nutrient-rich food, which in turn sustains rich organic matter that improves nutrient availability. In the following ways, sustainable diets can improve soil health:

1. By choosing locally grown foods, which reduces transportation impact and supports farms that maintain healthy local soils.
2. By reducing food waste, which helps in minimising pressure on land resources and prevents unnecessary soil degradation.
3. By composting kitchen waste, which returns organic matter to the soil, enriching it with nutrients and microbes.
4. Supporting organic and seasonal produce helps to encourage farming practices that protect soil biodiversity and fertility.
5. Growing home gardens, which promote soil conservation through natural compost use and minimal chemical inputs.

Soil is a dynamic natural body composed of minerals (45%), organic matter (5%), water (25%) and air (25%). It is the thin, uppermost layer of the Earth's crust that forms the essential medium for plant growth. Soil is not merely a growing medium, but a living ecosystem that supports plant growth, nutrient cycling, and water regulation. Degraded soils primarily affect human nutrition by diminishing both the quantity and quality of the food supply, leading to widespread malnutrition. When soil degrades through erosion, loss of organic matter or nutrient depletion, its capacity to sustain crops is severely reduced, resulting in lower agricultural yields and contributing to global food insecurity. More critically, healthy soil serves as a natural reservoir for essential micronutrients, including iron (Fe), zinc (Zn), and selenium (Se). Degraded soil is often deficient in these minerals, which means the crops grown on it, even staple foods like wheat and rice, absorb fewer nutrients. This phenomenon, known as "nutritional dilution", results in food that is calorie-rich but micronutrient-poor. Consequently, consuming this food leads to "hidden hunger", a form of malnutrition where individuals suffer from chronic micronutrient deficiencies without showing signs of calorie starvation. These deficiencies have severe public health consequences, including impaired immune function, anaemia and reduced cognitive development and general developmental issues, disproportionately impacting children and women in affected regions. In addition, some degraded soils may harbour or release toxic elements that crops can absorb, further compromising human health.

Household Ways to improve soil health around residential areas

1. Use kitchen scraps and garden waste to make compost that enriches soil fertility.
2. Mulch regularly by applying dry leaves or grass clippings to retain moisture and add organic matter.
3. Avoid chemical inputs by limiting the use of synthetic fertilisers and pesticides to protect soil microbes.
4. Grow native and diverse plants which will support soil structure and biodiversity with local species.
5. Harvest and collect rainwater for watering plants to prevent erosion and nutrient loss.

The Global Food Security Index (GFSI) indicates that the global food environment is deteriorating, marking a concerning reversal after reaching its peak in 2019. This decline is characterised by skyrocketing food prices and unprecedented levels of hunger. Based on 11 years of data, the index shows that the food system has been weakening structurally for years. This fragility was acutely exposed by recent shocks (2020-2022), notably the COVID-19 pandemic and high commodity prices.

Agroecology is a holistic, system-based approach that applies ecological and social principles to the design and management of food systems. It uniquely bridges the gap between environmental sustainability, food security, and nutrition by shifting the focus from simply maximising single crop yields to optimising the entire farm ecosystem. It is an approach to growing food which aims to address all of these problems within the food system. A holistic method, agroecology utilises ecological principles to produce food, including improving soil health, increasing biodiversity, and building synergies among different parts of the food system. It also focuses on the social, economic and political aspects of the food system. Agroecological principles also include co-creating agricultural knowledge with food producers, reconnecting producers and consumers, and ensuring that food systems are culturally appropriate and fair. Agroecology is a holistic approach that uses ecological principles (like increasing biodiversity and improving soil health) alongside social and economic tenets (like addressing gender inequity and promoting local markets) to solve systemic food problems, including hunger and overnutrition. The majority of studies reported positive relationships with outcomes like improved dietary diversity and child growth. It has been observed that complex interventions combining three or more agroecological practices (i.e., farm diversification, soil management and social components) were more likely to yield positive and robust impacts. This success occurs through multiple pathways, including the direct consumption of more diverse nutrient-rich food and economic benefits from reduced input costs and stable yields. The findings support agroecology as a crucial approach for transforming the global food system. The current downward trend, following eight years of early growth, reflects significant systemic issues that threaten food security and weaken the system's resilience. These structural risks include:

- Volatile agricultural production
- Scarcity of natural resources
- Increasing economic inequality
- Trade and supply-chain volatility

Table 1: Overall food security environment: the top and bottom ranking countries in 2022

Best performers	2022 score
Finland	83.7
Ireland	81.7
Norway	80.5
France	80.2
Netherlands	80.1
Japan	79.5
Canada	79.1
Sweden	79.1
United Kingdom	78.8
Portugal	78.7

Weakest performers	2022 score
Syria	36.3
Haiti	38.5
Yemen	40.1
Sierra Leone	40.5
Madagascar	40.6
Burundi	40.6
Nigeria	42
Venezuela	42.6
Sudan	42.8
Congo (Dem. Rep.)	43

Source: The Economist Group 2022

Achieving a sustainable food system requires a holistic approach driven by political will to integrate all sectors, comprising governments, businesses, consumers, and NGOs. High-level initiatives are being formed by the United Nations, the World Bank, and G7 nations to coordinate action. Critically, these efforts must involve the private sector leveraging its innovation and technology. Finally, GFSI data confirm that strong food security outcomes are linked to key interventions, including ensuring farmers have access to agricultural inputs and financial products, government investment in research and development, and innovative technology, as well as bolstering supply-chain infrastructure. The empowerment of female farmers shows one of the most significant positive impacts.

Conclusion

Building long-term, systemic resilience is paramount to reversing the global trend of increasing food insecurity, requiring a flexible mix of robustness, recovery, reorientation, and reorganisation tailored to each context, as no single solution exists. The primary emphasis must be on strengthening the food supply and the environment that supports it, enabling producers to adapt to climate change through sustainable practices such as improving land management, increasing soil organic carbon, reducing pollution and food waste. This adaptation focus is clearly reflected in the Global Food Security Index, where the most significant recent gains are in political commitments to adaptation, including steep rises in environmental economic accounting, risk management coordination, and climate finance.

Role of Methanotrophs in Reduction of Greenhouse Gas Emissions from Anthropogenic Activities

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Abstract

Methane (CH_4) is a potent greenhouse gas with a global warming potential considerably greater than that of carbon dioxide (CO_2). A significant amount of atmospheric methane is derived from human activities, including agriculture, waste management, and fossil fuel extraction. Methanotrophs, a specialised category of bacteria that oxidise methane into carbon dioxide, are essential for reducing methane emissions from various sources. This article establishes the ecological importance of methanotrophs, their methane oxidation mechanisms, and their role in mitigating greenhouse gas emissions from anthropogenic sources. It also emphasises recent advances in biotechnology and the practical applications of methanotrophs as an effective tool for climate change mitigation.

Keywords: Methanotrophs, Greenhouse gas, Methane emission, Anthropogenic activities, and Climate Change Mitigation.

1. Introduction

After carbon dioxide (CO_2), methane (CH_4) is the second most abundant greenhouse gas in the atmosphere. Atmospheric CH_4 concentrations have risen significantly from 700 to 1803 parts per billion since the pre-Industrial era. At the molecular level, the global warming potential of CH_4 is approximately 25 times greater than that of CO_2, contributing roughly 25% to global warming. Methane accounts for roughly 16% of total greenhouse gas emissions and possesses a global warming potential (GWP) that is 28-34 times greater than that of CO_2 over a century (IPCC, 2021). Human activities, especially rice cultivation, livestock farming, landfill operations, and fossil fuel extraction, significantly contribute to methane emissions (Saunois et al., 2020).

Methanotrophic bacteria, or methanotrophs, utilise methane as their exclusive carbon and energy source in aerobic environments. These microorganisms occupy a variety of ecosystems, such as soil, wetlands, rice paddies, and aquatic environments. Methane is derived from abiogenic, thermogenic, and biogenic microbial sources. This study examines biogenic methanogenesis by methanogenic archaea, which produce methane as a byproduct of the biological decomposition of organic matter for energy conservation. Approximately 70% of all sources of methane emissions to the atmosphere are methanogenic archaea, which can be found in a variety of settings, including wetlands, peatlands, rice agricultural soil, livestock (enteric fermentation in ruminants), landfills, seas, and termites (Guerrero et al., 2021). Effective agricultural water and fertiliser management practices are essential for reducing CH4 emissions while sustaining rice yields (Gu et al., 2021). It is essential to capture and reduce methane emissions from these sources and other anthropogenic activities. Various mitigation strategies and practices are employed globally to address this issue. Numerous technologies and practices mitigate various volatile and hazardous air pollutants in addition to methane. Mitigating methane emissions is essential for addressing climate change, energy stability, and public health security. Significant reductions can be attained by ceasing or diminishing activities, including altering the utilisation of coal and gas as energy sources and reducing ruminant emissions (Rani et al., 2024). This study examines the function of methanotrophs in the biological reduction of methane emissions originating from human activities.

2. Methanotrophs: Classification and Mechanism

2.1 Classification

Methanotrophs are classified into two major types based on their phylogeny and carbon assimilation pathways:

Type	Taxonomic Class	Pathway	Example Genera
Type I	Gammaproteobacteria	Ribulose Monophosphate (RuMP)	*Methylomonas*, *Methylobacter*, *Methylococcus*
Type II	Alphaproteobacteria	Serine Pathway	*Methylocystis*, *Methylosinus*

(Source: Hanson & Hanson, 1996)

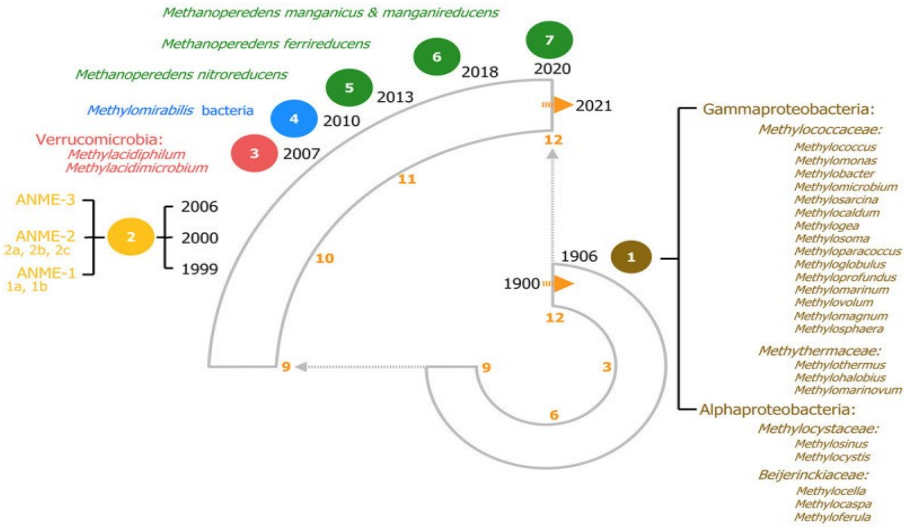

Fig.1 The most relevant findings are depicted highlighting all recognized methanotrophic groups categorized according to their phylogenetic classification. (Source: Guerrero et al., 2021)

- In brown, the discovery of aerobic canonical methanotrophy in 1906. On the right, all the known genera according to phylogenetic classification are listed.
- In yellow, the discovery of sulfate-dependent anaerobic oxidation of methane (S-dAOM). This process is performed by three defined groups of AN-aerobic ME-thanotrophic archaea

(ANME) within the Euryarchaeota phylum.

- In red, aerobic methanotrophy within the Verrucomicrobia phylum.
- In blue, nitrate-dependent anaerobic oxidation of methane (N-dAOM) by Methylomirabilis bacteria.
- (5-7) In green, nitrate-, iron-, and manganese-dependent anaerobic oxidation (N-dAOM and Metal-dAOM) of methane by diverse cultured species of the Methanoperedenaceae family.

2.2 Methane Oxidation Mechanism

Methanotrophs oxidize methane via the **methane monooxygenase (MMO)** enzyme. There are two types:

- **Particulate MMO (pMMO):** membrane-bound, most common.
- **Soluble MMO (sMMO):** cytoplasmic, expressed under copper-limited conditions.

Methane oxidation process: $CH_4 \rightarrow CH_3OH \rightarrow HCHO \rightarrow HCOOH \rightarrow CO_2$
This aerobic oxidation converts methane into less harmful carbon dioxide, thereby reducing its GWP impact.

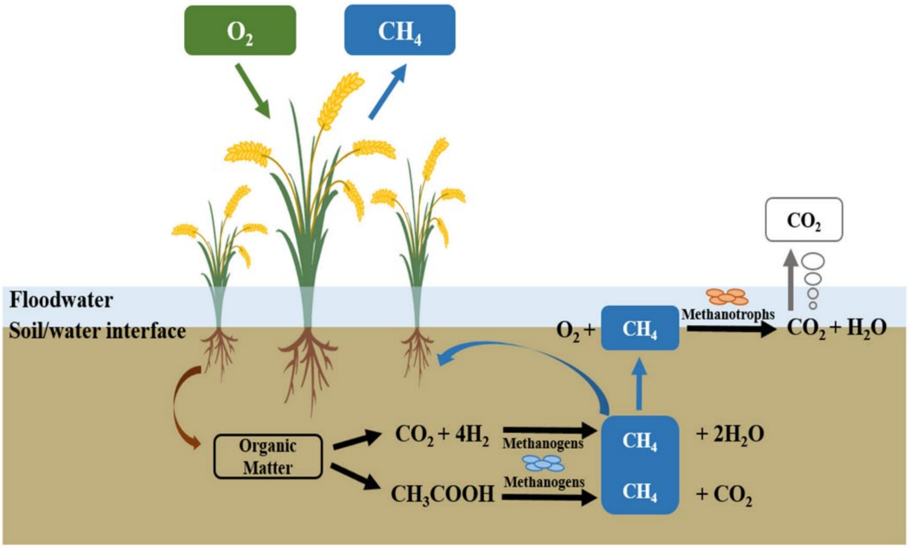

Fig. 2 Three processes of CH_4 in paddy soils

CH_4 is first produced in the anaerobic environment by methanogens, then transported to the soil–water interface and the rice rhizosphere, and can then be oxidized by methanotrophs in an aerobic environment before being released into the atmosphere. (Source: Gu et al., 2021).

3. Anthropogenic Methane Sources and Methanotroph-Based Mitigation

3.1 Major Anthropogenic Sources (Source: Saunois et al., 2020)

Source	Methane Emission Contribution
Agriculture (Rice fields, Livestock)	~40%
Landfills	~20%
Fossil fuel production and use	~35%
Biomass burning	~5%

3.2 Methanotroph Applications

- **Rice Cultivation**: Methanotrophs colonize the oxic zone of rice paddies and rhizosphere, oxidizing up to 90% of methane before it reaches the atmosphere (Singh et al., 2010).
- **Landfill Biocovers and Biofilters**: Soil layers inoculated with methanotrophs enhance methane oxidation in landfill covers, reducing emissions by 20-100% (Gebert & Gröngröft, 2006).
- **Livestock Waste Management**: Methanotroph-based composting systems mitigate methane release during manure decomposition.

4. Recent Advances and Future Perspectives

- **Genetic Engineering**: Development of high-affinity methanotroph strains with enhanced methane oxidation rates.
- **Methanotroph-Biochar Systems**: Integration of biochar as a habitat for methanotrophs in soils and compost piles improves methane mitigation.
- **Methanotroph Biofilms**: Biofilms on constructed wetlands and water treatment systems help in continuous methane removal.
- **Methane Utilisation Technologies:** Coupling methanotroph-based systems with bioproduct generation, like methanol and single-cell protein (SCP), offers dual environmental and economic benefits.

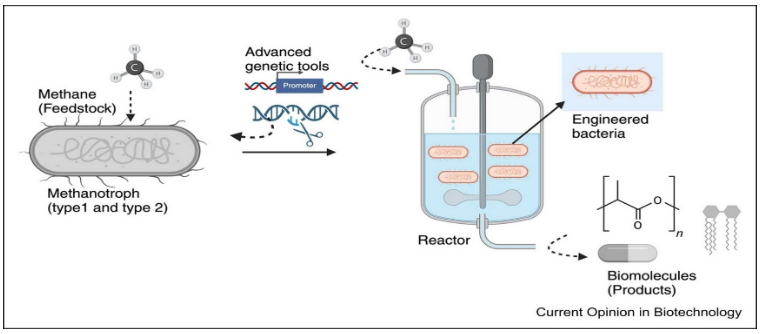

Fig. 3 Methane to bioproducts (Source: Tan et al., 2024).

5. Conclusion

Methanotrophs mitigate CH_4 emissions by consuming this potent greenhouse gas, thereby functioning as an effective carbon sink. The promise of methanotrophs as hosts for industrial biomanufacturing remains unrealised, mainly due to their environmental advantages. Methanotrophs serve as an environmentally sustainable method for reducing methane emissions originating from human activities. The capacity to biologically oxidise methane prior to its release into the atmosphere can substantially aid strategies aimed at mitigating global climate change. Additional investigation into the optimisation of methanotroph activity, strain enhancement, and field applications may improve their practical utility across multiple sectors.

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Renewables: The Silent Revolution

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Abstract
The growing dependence on fossil fuels for energy generation, transportation, and industrial activities has resulted in severe environmental and health challenges, including global warming, climate change, and air pollution. These conventional energy sources, though historically cost-effective and energy-dense, have become unsustainable due to greenhouse gas emissions and resource depletion. Transitioning to green energy is crucial for ensuring energy security, resilience, and environmental protection. Green or renewable energy—derived from solar, wind, hydroelectric, and geothermal sources—offers a sustainable alternative by providing clean, renewable power with minimal ecological impact. Each renewable source contributes uniquely: solar energy supports electricity generation and agricultural operations, hydroelectric power aids in flood control and irrigation, wind energy provides low-cost electricity, and geothermal energy enables sustainable heating and power generation. India has made notable progress by surpassing 200 GW of renewable energy capacity, with a target of 500 GW from non-fossil sources by 2030. However, challenges such as high initial investment, energy storage limitations, geographic dependency, and infrastructure requirements persist. Despite these constraints, renewable energy presents vast opportunities for rural and agricultural advancement—enabling cost reduction, crop preservation, biogas production, and sustainable livelihoods. Strengthening policy support, awareness, and technological innovation will accelerate the transition toward a cleaner and more resilient energy future.

Introduction

We are heavily reliant on fossil fuels because they are a highly energy-dense and relatively inexpensive source of power with a long history of meeting various energy needs, including transportation, residential and commercial uses, electricity generation, and manufacturing. Historically, fossil fuels have been relatively inexpensive to extract and transport, especially in regions with large deposits. This makes them an attractive option for powering large-scale industrial processes and meeting energy demands, particularly in developing nations. However, burning these fossil fuels releases greenhouse gases, primarily carbon dioxide, which contributes to respiratory illnesses, cardiovascular problems, and other health issues, as well as environmental problems such as global warming and climate change. Reliance on fossil fuels creates vulnerability to price fluctuations and supply disruptions, particularly for countries that are dependent on imports. Fossil fuel-based road transport, industrial activity, and power generation (as well as the open burning of waste in many cities) are the most significant sources of air pollution and greenhouse gases globally. In many developing countries, the use of charcoal and wood for heating and cooking also contributes to poor indoor air quality. According to studies by the World Health Organisation, the presence of particles and other air pollutants in urban skies is responsible for substantial health impacts, millions of premature deaths, and staggering economic costs. Hence, there is a high need for dependence on green energy for energy security and resilience.

Green energy is electricity generated from natural resources, such as solar, wind, and hydropower, which are naturally replenished, offering low or zero greenhouse gas emissions compared to fossil fuels. These energy sources offer a cleaner, more sustainable alternative, thereby mitigating climate change, reducing pollution, and promoting economic development. Additionally, renewables offer benefits to societies, including improved energy access, job creation in local communities, enhanced energy security, and opportunities for community ownership and empowerment. Renewable energy sources produce significantly lower emissions throughout their entire lifecycle compared to fossil fuels. During their operation, they have minimal to no impact on both air quality and greenhouse gases. Replacing the current fossil fuel-based energy system with a renewables-based system is the most urgent and efficient way to tackle harmful emissions and air pollution.

Sources of renewable energy

i. Solar energy (Fig.1)

It is the radiant energy from the sun that can be harnessed to produce heat or electricity using various technologies. It's a renewable and virtually inexhaustible resource, making it a key component in the transition to cleaner energy sources. Solar energy can be used for a wide range of applications, including electricity generation, heating water, and providing comfortable indoor environments. Solar panels directly convert sunlight into electricity. This electricity can be used to power homes, businesses, and even entire communities. Solar energy can power water pumps for irrigation and other water supply needs, particularly in remote areas.

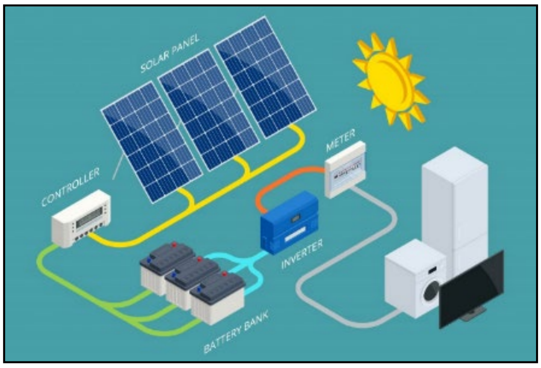

Fig. 1 Solar power plant

Solar dryers can be used to dry a wide range of agricultural products and other materials. It can also be used to desalinate seawater, providing a source of fresh water. Solar panels are used on satellites to power their onboard systems. Solar-powered lights can be used for streetlights, garden lights, and other outdoor lighting needs. For various agricultural purposes, including greenhouse heating, irrigation, and crop drying, this energy can be used. Solar process heat can be utilised in multiple industrial applications that require heat, including manufacturing and food processing.

ii. Hydroelectric energy (Fig.2)

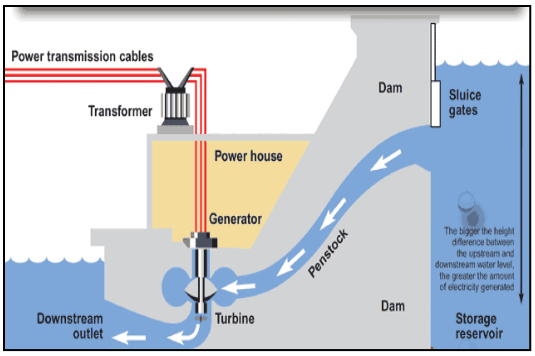

Fig. 2 Hydroelectric energy generation

Hydroelectric plants can support other renewable energy sources and offer benefits beyond electricity generation, such as flood control, irrigation, and water supply. Hydroelectric power relies on the water cycle, a naturally replenishing process, making it a renewable energy source. It doesn't consume water resources; the water used to generate electricity is returned to the river system. This helps reduce air pollution and mitigate climate change. Hydroelectric power plants can store excess energy by pumping water uphill into reservoirs, which can then be released to generate electricity when needed.

iii. Wind energy (Fig.3)

It's a low-cost source of electricity, particularly onshore wind. Wind energy development creates jobs in manufacturing, installation, operation, and maintenance of wind turbines. Wind energy supports sustainable development goals by providing clean energy and promoting a circular economy. Shifting wind energy can reduce the demand for fossil fuels, which are subject to price fluctuations and geopolitical instability.

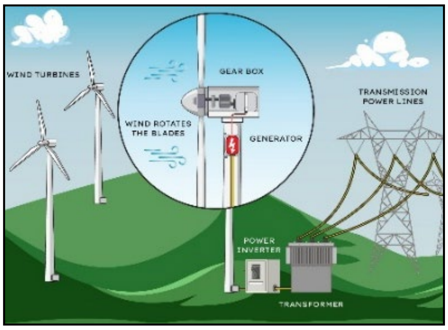

Fig. 3 Wind energy

iv. Geothermal energy (Fig.4)

The Earth's core and mantle contain immense heat from the planet's formation and the radioactive decay of elements like potassium, thorium, and uranium. This heat is transferred to the Earth's crust and can be found in underground reservoirs of hot water or steam. Wells are drilled into these reservoirs to bring hot water and steam to the surface. This energy can be utilised in electricity generation, while hot water can be used directly for heating buildings, bathing, or in industrial processes. Additionally, geothermal heat pumps can be employed for heating and cooling systems in homes and other buildings.

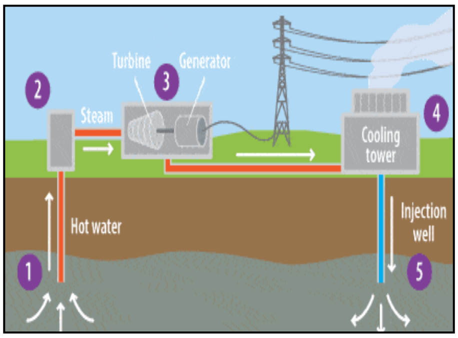

Fig. 4 Geothermal energy

India's contribution towards the use of renewable sources

India has reached a significant milestone in its renewable energy journey, with the country's total renewable energy capacity crossing 200 GW (gigawatt). This remarkable growth aligns with the country's ambitious renewable energy target of achieving 500 GW from non-fossil sources by 2030 (as per the report of the Ministry of New and Renewable Energy, Govt. of India). This milestone reflects the result of years of dedicated efforts to harness India's natural resources. From sprawling solar parks to wind farms and hydroelectric projects, the country has steadily built a diverse renewable energy base. These initiatives have not only reduced the nation's reliance on fossil fuels but also strengthened its energy security.

Limitations of green energy

- Significant initial capital investment is needed for building large-scale solar farms and wind turbines.
- Storing solar energy for winter or when the wind isn't blowing is expensive and requires space.
- Solar power generation is dependent on sunshine, and wind power on wind, leading to inconsistent power output.
- Renewable energy sources can be decentralised, requiring new and extensive transmission networks to move power from their generation to the distribution/utility end.
- Wind and solar energy require specific geographic locations with consistent wind or sun.
- Renewable energy installations like wind farms and large-scale solar arrays often require extensive amounts of land.
- While operational renewable systems have a low carbon footprint, their manufacturing, transport, and installation stages do generate greenhouse gases.
- Production of renewable energy technologies relies on certain materials, potentially facing supply chain limitations.
- In some areas, a lack of knowledge, consistent policies, and financial incentives can hinder green energy development.

Conclusion

Renewable energy resources offer farmers a pathway to reduced costs, increased energy independence, and a smaller environmental footprint. Solar power, wind energy, and biomass are among the most promising options, enabling farmers to generate electricity, heat water, and power machinery while reducing reliance on fossil fuels. Solar dryers can be used to preserve crops, such as fruits and vegetables, thereby extending their shelf life and reducing post-harvest losses. Wind-powered water pumps can be used for irrigation and livestock watering. Anaerobic digestion of agricultural waste (manure, crop residues) can produce biogas, a renewable fuel that can be used for heating, electricity generation, or even transportation. Many governments offer incentives, such as tax credits and grants, to encourage the adoption of renewable energy in agriculture.

Role of non-coding RNA in modulating plant immune responses

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Abstract

Diseases pose a significant threat to rice cultivation, leading to substantial yield losses and endangering global food security. To defend against pathogens, plants have evolved a range of intricate defence mechanisms. Early research on plant–pathogen interactions primarily focused on identifying resistance and pathogenicity genes and elucidating their roles in host defence. Subsequently, the importance of regulatory molecules such as transcription factors in coordinating plant defence responses was recognised. With advancements in molecular research, non-coding RNAs (ncRNAs) have emerged as crucial regulators of plant immunity. This review highlights the roles and interactions of microRNAs (miRNAs), long non-coding RNAs (lncRNAs), and small interfering RNAs (siRNAs) in modulating immune responses in cultivated plants. The complex regulatory relationships between ncRNAs and their target genes are discussed in depth.

Keywords: ncRNA; miRNA; sRNA; lncRNA; plant immunity

Introduction

Plants, being immobile, are continually exposed to pathogens such as bacteria, fungi, and viruses. To defend themselves, they have developed two major immune layers: pathogen-associated molecular pattern (PAMP)-triggered immunity (PTI) and effector-triggered immunity (ETI). In PTI, membrane-bound pattern recognition receptors (PRRs) detect pathogen molecules and activate basal defence responses. ETI, on the other hand, is mediated by intracellular resistance (R) proteins, mainly NLRs, which recognise specific pathogen effectors and trigger strong immune reactions. Both PTI and ETI share overlapping signaling pathways and downstream responses. Plant immunity can be further described as a three-layered system: the recognition layer (pathogen detection by PRRs and intracellular receptors), the signal-integration layer (transmission of defence signals), and the defence-action layer (activation of responses such as callose deposition, ROS generation, and pathogenesis-related gene expression).

Non-coding RNAs (ncRNAs) play a crucial regulatory role in modulating plant immune responses against various pathogens, including viruses, bacteria, fungi, and nematodes. Advances in high-throughput sequencing and transcriptomic studies have revealed that much of the eukaryotic genome is transcribed into non-coding

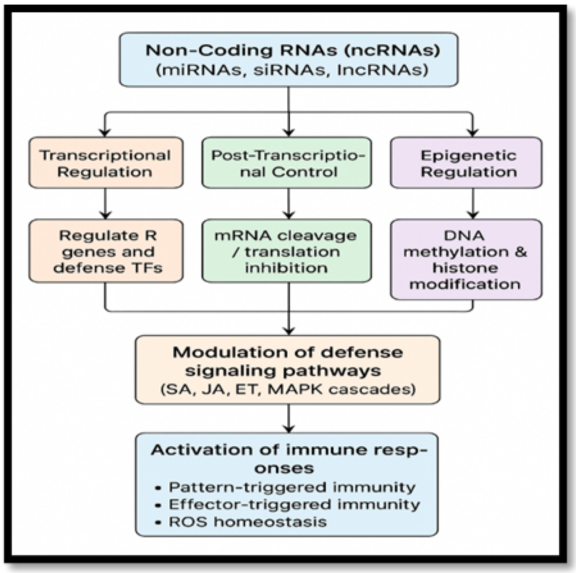

Fig. 1: Classification of non-coding RNAs

RNAs (ncRNAs), which do not encode proteins. Based on length, ncRNAs are classified as small (18–30 nt), medium (31–200 nt), and long (>200 nt) . In plants, the main small RNAs are microRNAs (miRNAs) and small interfering RNAs (siRNAs). miRNAs (21–24 nt) arise from imperfect hairpin precursors, while siRNAs originate from perfectly complementary double-stranded RNAs synthesized with RNA-dependent RNA polymerases (Borges and Martienssen, 2015). Another emerging group, circular RNAs (circRNAs), are formed by back-splicing that covalently joins the 3′ and 5′ ends of pre-mRNA into a closed loop (Patop *et al*., 2019).

ncRNAs involved in regulating components of immune recognition and signal transduction

Plant immune receptors include **membrane-bound PRRs** mediating PTI and **cytoplasmic NLRs** mediating ETI, both tightly regulated by **non-coding RNAs (ncRNAs)**. Many **miRNAs** control **NLR gene expression** to balance defense and growth—some trigger phasiRNAs (e.g., miR472, miR2118, miR9863), while others directly cleave NLR mRNAs (e.g., miR1510, Md-miRLn11). ncRNAs also regulate **signal transduction**, as seen with miR172b enhancing FLS2 expression, miR863-3p silencing negative regulators, and circRNAs modulating receptor kinases. Additionally, several miRNAs (miR396, miR169, miR164a, miR156) target **transcription factors** that control defense gene expression. Overall, ncRNAs fine-tune **immune perception, signaling, and transcriptional reprogramming** to coordinate effective plant defense responses.

ncRNAs that regulate the production of defense markers, hormone biosynthesis and signaling, or RNA-mediated silencing

Many non-coding RNAs (ncRNAs) regulate plant immunity through modulation of ROS production, PR gene expression, callose deposition, hormone signaling, and RNA-silencing pathways.

- **ROS regulation:** miR400, miR398b, and miR528 in Arabidopsis and rice alter ROS levels by targeting genes for ROS metabolism, affecting resistance to *Pst*, *Botrytis cinerea*, and *Magnaporthe oryzae*. Tomato lncRNAs (lncRNA16397, lncRNA33732) modulate ROS-related genes (GRX, RBOH) during *Phytophthora infestans* infection.

- **PR gene induction:** ncRNAs such as miR393*, miR163, and lncRNA ELENA1 in Arabidopsis, osa-miR7695 in rice, and lncRNA39026 or circR5g05160 in tomato regulate PR gene expression, enhancing pathogen resistance.
- **Callose deposition:** miR773, miR398b, and miR160a affect callose formation and thus pathogen entry resistance.
- **Hormone signaling:** ncRNAs fine-tune pathways of auxin (miR393), ethylene (miR166k-166h), JA (miR319, ALEX1), and SA (miR477), influencing responses to *Xoo*, *V. dahliae*, and *B. cinerea*.
- **RNA silencing machinery:** miR863-3p, AGO18, miR444, and miR403 regulate RISC and RNA processing components, impacting antiviral and antibacterial immunity.

The coordinated function of miRNAs, siRNAs, lncRNAs, and circRNAs

1.miRNAs and siRNAs

miRNAs and siRNAs are small RNAs processed by Dicer/Dicer-like (DCL) enzymes and loaded into Argonaute (AGO) proteins to silence target mRNAs through sequence complementarity. Some miRNAs, especially 22-nt miRNAs, initiate the production of secondary siRNAs such as tasiRNAs and phasiRNAs via the coordinated action of RDR6, SGS3, SDE5, DCL4, and AGO1. These secondary siRNAs amplify silencing signals—tasiRNAs act in *trans* to silence unrelated genes, while phasiRNAs act *in cis* on their source transcripts. A conserved group of miRNAs (mainly the miR482/2118 family) targets NLR (R genes) to produce phasiRNAs, thereby fine-tuning NLR expression and preventing autoimmunity in the absence of pathogens. For example, in *Brassica rapa*, miR1885 targets both an NLR gene (*BraTNL1*) and a silencing gene (*BraTIR1*), generating different phasiRNAs and tasiRNAs that coordinate disease resistance and developmental processes. Thus, miRNA–siRNA cascades form a multi-layered regulatory network that balances immune defense with plant growth.

2.lncRNAs and miRNAs or siRNAs

lncRNAs play diverse roles in plant immunity by acting as precursors, decoys, or targets of small RNAs. Some lncRNAs function as precursors for miRNAs and siRNAs, contributing to pathogen-responsive gene silencing. For example, in *wheat* and *Brassica napus*, lncRNAs serve as precursors for multiple immune-related miRNAs (e.g., miR156, miR169), while in *mulberry*, the miR3954–MuLnc1–siRNA–mRNA module regulates defense through silencing of *CML27*. lncRNAs can also act as competitive endogenous RNAs (ceRNAs), mimicking miRNA targets to sequester miRNAs and modulate resistance. In *tomato*, several lncRNAs (e.g., lnc0195, lnc39026, lnc23468) act as decoys for miR166, miR168, or miR482b, thereby upregulating NLR and defense-related genes against *Phytophthora infestans* and *TYLCV*. Moreover, mutual regulation between lncRNAs and small RNAs fine-tunes immunity. For instance, *Sl-lncRNA15492* and *Sl-miR482a* negatively regulate each other to balance NLR gene (*Sl-NBS-LRR1*) expression during *P. infestans* infection. Similarly, viral siRNAs can directly cleave host lncRNAs (e.g., *SlLNR1* in tomato), integrating host–pathogen regulatory interactions.

3.circRNAs and miRNAs

In plants, the role of circRNAs as miRNA sponges remains uncertain. Unlike in animals, most plant circRNAs lack multiple miRNA-binding sites and are unlikely to function as effective sponges. Only a small fraction in *Arabidopsis* (5%) and *rice* (6.6%) show potential miRNA interactions, and experimental evidence (e.g., *Os08circ16564*–miR172) suggests limited functional relevance. Structural constraints and low circRNA abundance may further restrict their sponge activity. However, some circRNAs, such as circRNA45 and circRNA47 in *tomato*, are induced during *P. infestans* infection and may modulate immunity by sequestering specific miRNAs, though this requires more validation.

Additionally, pathogen effectors can hijack plant RNA-silencing machinery to suppress immunity. Viral proteins (e.g., P19), bacterial effectors (e.g., HopT1-1), fungal suppressors (PgtSR1), and oomycete proteins (PSR1, PSR2) interfere with small RNA pathways by targeting miRNA or AGO components, thereby weakening plant defense. This reflects a conserved pathogenic strategy to overcome RNA-based immunity in host plants.

Future perspectives and Conclusion

A growing number of plant non-coding RNAs (ncRNAs) have been discovered to participate in plant immune regulation, yet the precise molecular mechanisms underlying their actions remain largely unclear. Current evidence indicates that ncRNAs are key regulators of various phases of plant immunity, including pathogen recognition, signal transduction, and defense activation. These molecules employ multiple strategies—such as modulating gene expression, binding to proteins, and interacting with other ncRNAs—to fine-tune immune responses (Sui *et al*., 2020). Recent research has revealed that mobile non-coding RNAs (ncRNAs) can move between plants and their pathogens, enabling cross-kingdom communication that influences both plant immunity and pathogen virulence (*Weiberg et al*., 2013; Wang *et al*., 2016b; Zhang *et al*., 2016c; Cai *et al*., 2018; Huang *et al*., 2019). Identifying the target genes and elucidating the molecular mechanisms regulated by these mobile ncRNAs are crucial for understanding their roles in host–pathogen interactions. Moreover, since ncRNAs occupy diverse subcellular compartments, their localization patterns likely correspond to distinct biological functions. Therefore, determining the subcellular localization of specific ncRNAs is essential for uncovering how they contribute to plant immune regulation.

Because a single ncRNA can influence several target genes, it often exerts pleiotropic effects, impacting not only immunity but also plant growth, development, and abiotic stress responses. For example, in *Brassica*, miR1885 regulates both defense and growth by repressing the NLR gene BraTNL1 and the photosynthesis-related gene BraCP24, making it a potential target for breeding crops with improved disease resistance and yield. Conversely, some genes are simultaneously regulated by multiple ncRNAs, reflecting the complex and interconnected regulatory networks that maintain the balance between immune protection and normal development.

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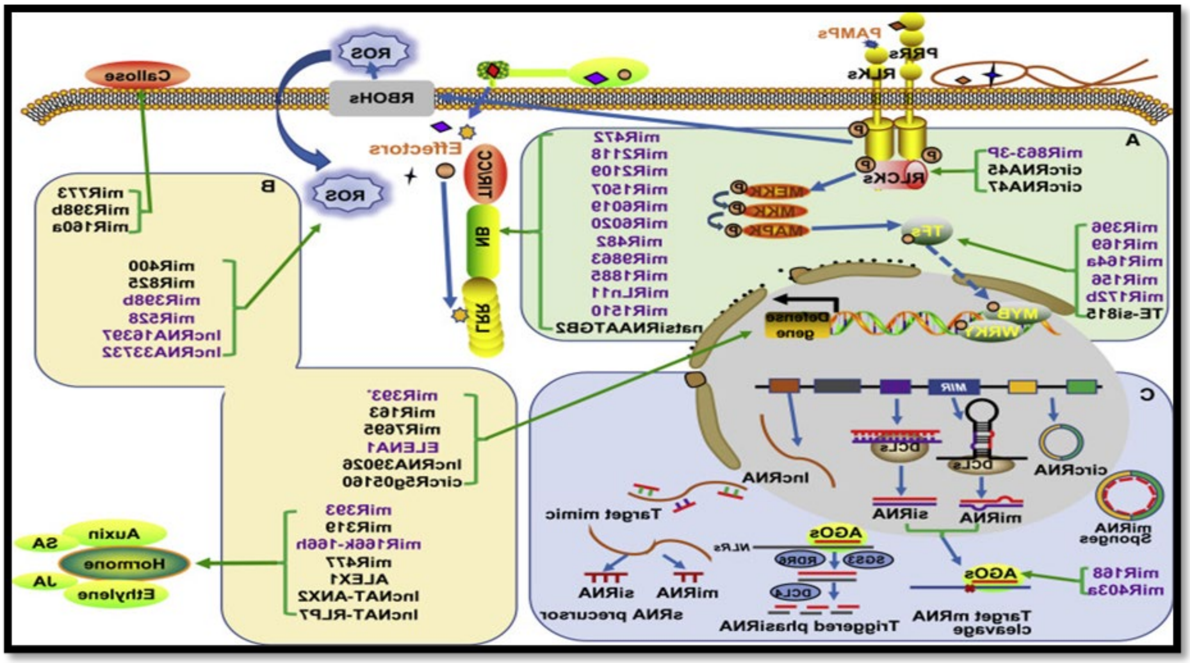

Fig. 2: ncRNAs involved in plant immunity and their underlying regulation

Seedborne mycotoxins and food safety: how farmers can prevent contamination

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Abstract

Seedborne mycotoxins- toxic secondary metabolites produced by seed-associated fungi such as *Aspergillus* and *Fusarium* are hidden but serious threat to food safety and seed health. This article explains how mycotoxins contaminate seed, identifies field-to-store risk points and gives practical, seed-pathology focused recommendations farmers can adopt to reduce contamination at every stage: varietal selection, crop management, harvesting, drying and seed storage, testing and participation in formal seed certification systems. Evidence-based best practices and detection options are summarized so extension agents and seed producers can implement affordable, effective controls.

Why seedborne mycotoxins matter

Seeds can carry fungal pathogens on the surface or inside tissues; some of those fungi produce mycotoxins (e.g., aflatoxins from *Aspergillus* spp., fumonisins and trichothecenes from *Fusarium* spp.). When contaminated seed is planted, milled or fed to livestock, mycotoxins move into food and feed chains, causing acute and chronic health effects and economic losses. Seed lots used for planting or for human/animal consumption therefore represent a critical control point for preventing wider contamination. Surveillance studies consistently find *Aspergillus* and *Fusarium* as dominant seed fungi in many crops, highlighting the need for seed-level interventions (Sivakaame *et al*., 2025). For example, Aspergillus flavus when infect groundnut seeds (Figure 1), it can produce aflatoxin.

Fig. 1. Groundnut seed infected with *Aspergillus flavus*

Source of contamination

1. **Pre-harvest infection**: Toxigenic fungi infect crops in the field under warm, humid or drought-stressed conditions. Crops stressed by drought or insect damage have higher fungal colonization and toxin accumulation (Pandey *et al.*, 2023).
2. **Harvest timing and practices**: Late or uneven harvests leave some seed/fruit exposed to fungi;

mechanical damage increases vulnerability.

3. **Drying and conditioning**: Slow or inadequate drying allows fungi to grow and produce toxins after harvest. So, proper moisture reduction becomes crucial immediately after harvest.
4. **Storage and transport**: High moisture, poor aeration, warm temperature and insect activity in storage accelerate fungal growth and mycotoxin formation. (Matumba *et al.*, 2021).
5. **Seed multiplication and trade**: Moving seed between regions without proper phytosanitary checks spreads infected lots; seed certification reduces this risk.

On-farm prevention: practical seed-pathology measures farmers can adopt

Below are concrete actions organized by the crop production cycle.

A. Before planting: seed selection & health

- **Use certified seed**. Certified seed undergoes inspection and testing that reduce seedborne pathogens and poor-quality lots. Certification schemes and phytosanitary standards describe sampling and testing protocols for seed health.
- **Prefer tolerant/resistant varieties**. Breeding for resistance to fungal colonization reduces overall toxin risk; where available, choose varieties known to resist *Aspergillus*/*Fusarium* infections (Zadravec *et al.,* 2022).

B. In the field: cultural and integrated measures

- **Crop rotation and residue management.** Rotate away from host crops to reduce inoculum in soil and destroy crop residues that shelter fungi.
- **Planting time and density.** Adjust sowing dates and plant density to avoid peak conditions favorable to fungi (for instance, extreme heat and drought around flowering) (Pandey *et al.*, 2023).
- **Control insect pests.** Insects cause wounds that allow fungal entry; integrated pest management reduces this pathway.

C. Harvesting: timing and handling

- **Harvest at optimal maturity and promptly.** Avoid delays that leave seeds exposed to weather or pests. Use gentle handling to minimize mechanical damage.

D. Drying, cleaning and seed conditioning

- **Rapid, thorough drying** to moisture level safe for seeds and storage (crop-specific; typically, <12–14% for many cereals and oilseeds). Drying stops fungal growth and mycotoxin production.
- **Physical separation and cleaning.** Remove broken, shrivelled, discoloured seeds, weed seeds and foreign material that concentrate fungi and toxins. Simple winnowing, gravity separators and sieves are effective first steps.

E. Storage and transport

- **Maintain low moisture and cool temperatures.** Use clean, dry, well-ventilated storage (silos, hermetic bags) and monitor moisture and temperature. Solar dryers can be low-cost options for smallholders.

- **Manage insects and rodents.** Keep storage insect-free; fumigation or integrated pest control prevents damage that leads to fungal growth.

Monitoring and detection

Regularly testing seed lots for mycotoxins helps catch contamination early. Options range by cost and complexity:

- **Lateral flow devices**: Quick, on-site screening for aflatoxin and other common mycotoxins; results in minutes and increasingly quantitative. Useful for routine lot screening before marketing or storage (Sadeghi *et al.,* 2024).
- **ELISA kits**: ELISA (Enzyme-Linked Immunosorbent Assay) kits are widely available and used for the rapid, sensitive, and cost-effective detection and quantification of numerous mycotoxins in various foods.
- **Chromatography (HPLC/LC-MS/MS)**: Best for confirmation and multi-mycotoxin profiling but requires central labs. Use for a periodic survey.
- Extension services or seed certification agencies can help smallholders access testing; cost-effective screening combined with targeted lab confirmation can be helpful.

Remediation and risk-reduction for contaminated lots

- **Physical sorting and removal**: Removing visibly affected seed reduces mycotoxin load. Manual or mechanical separation is often the most accessible mitigation (Goyal,1992).
- **Dilution and diversion**: Toxins cannot be completely removed by dilution and this is not recommended for food/feed destined for humans or monogastric animals; contaminated lots should be diverted to non-food uses only under regulatory guidance.
- **Biocontrol & post-harvest treatments**: Research supports biocontrol agents and adsorbents/processing methods to reduce toxin transfer, but farmers should follow approved, locally recommended practices.

Seed certification, standards and the farmer's role

Participating in certified seed systems, following national seed standards and phytosanitary procedures and maintaining records (harvest dates, drying, storage conditions, treatments) significantly reduces the risk of distributing contaminated seed. National and international codes of practice (FAO/Codex, IPPC RSPMs, national seed standards) provide frameworks for sampling, testing and seed movement that protect both seed health and public food safety. Farmers should work with seed certification agencies and extension services to meet these standards.

Key takeaways for farmers

- Use certified, clean seed and resistant varieties where possible.
- Minimise field stress: good agronomy, pest control, crop rotation and residue management.
- Harvest timely, dry rapidly to save moisture, clean and sort seed thoroughly (Matumba *et al.,*2021).
- Store in clean, dry, ventilated or hermetic conditions; monitor moisture/temperature.
- Screen lots regularly with rapid tests and use laboratory confirmation when needed.
- Engage with seed certification and local extension for testing, training and market access.

Conclusion

Preventing seedborne mycotoxins is a seed-pathology problem that requires actions at every step, from varietal choice and field management to drying, seed conditioning, storage and testing. Many preventive steps are low-tech and affordable (timely harvest, sun/solar drying, cleaning, hermetic storage, simple on-farm tests). Combining good agricultural practice, good storage practice, and participation in certified seed systems offers the most reliable route to reducing mycotoxin risk and protecting food safety for farmers and consumers alike. Where capacity is limited, pragmatic solutions (cleaning, drying, hermetic bags, on-site rapid tests) provide immediate benefits while national programs and extension services scale laboratories and certification support.

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Integrating Science and Sustainability: Approaches for Fungal Disease Management in mungbean

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Abstract

Mungbean (*Vigna radiata var. radiata*), a significant legume crop in South and Southeast Asia, is badly impacted by fungal infections that lower its output. Powdery mildew, anthracnose, Cercospora leaf spot, Fusarium wilt, Rhizoctonia root rot and web blight, and Macrophomina charcoal rot are some of the most common fungal infections. There are a few sources of resistance, particularly for Rhizoctonia and Macrophomina, marker-assisted selection can benefit from QTLs and R genes found for powdery mildew and Cercospora leaf spot. The emphasis is on integrated disease management, which combines plant extracts, fungicides, biocontrol agents, host resistance, and cultural practices. Systemic acquired resistance (SAR) is still poorly understood, however biocontrol-based induced systemic resistance (ISR) has been investigated. Field-level validation and commercial acceptance are scarce, despite the fact that many botanicals and biological agents show promise in lab and greenhouse settings. Therefore, sustainable long-term management of mungbean fungal diseases requires integrated strategies supported by extensive field research and the development of resistant cultivars.

Introduction

Mungbean, cultivated mainly in rain-fed regions of South and Southeast Asia, faces significant yield losses due to fungal diseases, exacerbated by climatic variability, including rising temperatures and CO_2 levels. Major soil-borne diseases like dry root rot (*Macrophomina phaseolina*) and Rhizoctonia root rot cause 11–44% yield losses, while foliar diseases like anthracnose, Cercospora leaf spot, powdery mildew, web blight, and Fusarium wilt are major production constraints. Cercospora leaf spot alone can cause 23–96% losses, anthracnose 24–67%, and powdery mildew up to 100% under severe conditions in India. Web blight results in 30–40% yield reduction, while *Rhizoctonia* infection can cause 20–40% seedling mortality. *Fusarium* wilt, once minor, now causes up to 80% losses in Australia. Changing climate patterns—higher temperatures, drought, and CO_2 levels—are intensifying soil-borne diseases such as *Macrophomina*, *Fusarium*,

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and *Rhizoctonia*. Though data on mungbean are limited, parallels with soybean, chickpea, and wheat suggest increased disease severity in warmer, drier environments. The unpredictable interactions among rainfall, temperature, and humidity under climate change complicate forecasting of foliar diseases. Hence, integrated management strategies and region-specific disease monitoring are crucial to mitigate the economic impact of fungal diseases in mungbean cultivation.

Perspectives for Sustainable Disease Management

Cultural and physical practices play a fundamental role in managing foliar and root rot diseases in mungbean. Field sanitation, crop rotation, removal of debris and weed hosts effectively relegate *Cercospora* blight, while removing infected plants lowers the sclerotia load of *Macrophomina phaseolina*. Delayed sowing and wider spacing facilitate minimising powdery mildew incidence. Plastic mulching aids sclerotial mortality of *Macrophomina phaseolina*, minimising infection. Seed treatments utilising gamma rays (60Co) restrain root rot fungi, and hot water treatment (55–65°C) eradicates seed-borne *Colletotrichum* infections. On the other hand, incessant rice–wheat–mungbean rotations have increased the prevalence of root rot due to shared pathogens such as *Rhizoctonia* and *Fusarium*. Diversifying crop rotations and integrating residue management and optimal planting dates are recommended for sustainable control of soil-borne diseases. In the context of climate change, such integrated cultural strategies enhance system resilience, minimise pathogen buildup, and promote long-term management of mungbean fungal diseases under a wide range of agro-ecological conditions.

Fungicide application remains the primary strategy for managing major mungbean fungal diseases, including Cercospora leaf spot, powdery mildew, anthracnose, and root rots. Effective fungicides include DMIs, MBCs, and SDHIs, with carbendazim, tridemorph, and flutolanil showing strong control. However, poor awareness by farmers, lack of economic evaluation, and weak regulatory frameworks in developing countries risk fungicide misuse and resistance development. Implementing FRAC-recommended resistance management, comprising rotating and mixing fungicides with varied modes of action, and developing eco-safe next-generation fungicides, is essential for sustainable disease control.

Reliable and efficient screening approaches have been utilized to identify resistance sources against major foliar and soil-borne fungal diseases of mungbean such as *Cercospora* leaf spot, powdery mildew, anthracnose, *Macrophomina* blight, and dry root rot. Screening can be done under natural high-disease field conditions or through artificial inoculation in greenhouse or laboratory setups. Standard disease rating scales expedite qualitative and quantitative assessment. For root rot and wilt diseases, due to genotype × environment interaction, screening is performed under controlled conditions using techniques like paper towel and sick pot/field inoculation with fungal cultures. Resistance sources have been acknowledged mainly for *Cercospora* leaf spot and powdery mildew, whereas reports on anthracnose and root rot are inadequate. Resistant materials have been obtained from cultivars, breeding lines, landraces, wild relatives, and mutant lines. These resistant sources perform as valuable donors for breeding disease-resistant mungbean varieties, though additional research is needed for lesser-studied pathogens.

Development of disease-resistant mungbean varieties relies on identifying resistance sources and molecular markers linked to major genes or QTL for marker-assisted selection (MAS). Major advancements have been realised for powdery mildew and *Cercospora* leaf spot. For powdery mildew, both qualitative (monogenic) and quantitative inheritance patterns have been reported, implicating single dominant genes (Pm1, Pm2, Pm3) and several QTLs, accounting for up to 58% of the phenotypic variation. SSR markers such as CEDG282, CEDG191, MB-SSR238, and CEDG166 are useful for MAS. QTLs identified on linkage groups 4, 6, and 9 further confirm the genetic basis of resistance. For *Cercospora* leaf spot, resistance is controlled by single dominant, recessive, or quantitative genes, with the major QTL qCLS mapped on LG3 between CEDG117 and VR393, accounting for 66–81% of the variation. However, no QTLs or markers have yet been identified for anthracnose and dry root rot, emphasising the need for expanded molecular studies for these diseases.

Biological control offers an eco-friendly alternative for managing fungal diseases of mungbean, particularly root-rot pathogens such as *Rhizoctonia solani*, *Macrophomina phaseolina*, and *Fusarium solani*. Biocontrol agents such as *Trichoderma viride*, *T. harzianum*, *Pseudomonas fluorescens*, *Bacillus subtilis*, and *Burkholderia spp.* have shown significant disease suppression (50–80%) and yield improvement in greenhouse and limited field trials. Integrated use of bioagents with organic amendments or vermicompost enhances efficacy. Combined formulations of *T. viride* + *P. fluorescens* effectively controlled *Macrophomina* root rot under field conditions. Botanical extracts and essential oils, including neem, *Allium spp.*, *Datura metel*, and palmarosa oil, showed fungicidal activity and up to 90% disease reduction in vitro and greenhouse studies. These plant products act through antifungal compounds like phenols and flavonoids. Induced systemic resistance (ISR) and systemic acquired resistance (SAR) play key roles in enhancing defence enzymes such as PO, PPO, PAL, and PR proteins. Treatments with *Pseudomonas fluorescens* and *Trichoderma* formulations enhanced these defence responses, reducing fungal infection severity. However, field validation and a deeper understanding of ISR and SAR mechanisms against fungal pathogens in mungbean are nonetheless in demand for large-scale application and commercial use.

Challenges

Sustainable disease management in mungbean production faces multiple challenges, predominantly in developing countries, where over 90% of the crop is grown by smallholders with inadequate knowledge of integrated pest management (IPM). Unconventional methods such as gamma irradiation for seed treatment remain unrealistic for small-scale farmers, while depleted national breeding programs and high pathogen variability hinder durable disease resistance. Resistance breakdown due to monogenic inheritance and linkage drag between desirable and undesirable traits adds to complicate breeding efforts. Fungicide misuse, non-rotation, and lack of awareness of resistance management can increase risks, potentially leading to fungicide resistance. Although biopesticides present eco-friendly alternatives, they often show inferior efficacy to chemical fungicides and encounter constraints like inconsistent field performance, poor adoption, and limited extension support. Likewise, interactions among bioagents can be antagonistic, shrinking effectiveness. Climate change intensifies these challenges by altering pathogen aggressiveness, host susceptibility, and disease dynamics, while also diminishing the efficacy of chemical and biological control measures. Developing climate-resilient, disease-resistant mungbean varieties and implementing region-specific IPM strategies integrating host resistance, fungicide stewardship, and eco-compatible biocontrol remain essential for realising sustainable disease management under changing climatic conditions.

Conclusion

Mungbean production is limited by major fungal diseases, including root rot, wilt, and foliar infections, across Asia. Integrated Disease Management (IDM) by coordinating host resistance, fungicides, and cultural practices remains the most effective strategy. However, weak research and extension linkages restrain technology transfer to farmers. Breeding for durable, climate-resilient resistance and validating molecular markers for key diseases are decisive future demands. Research gaps include fungicide sensitivity data, efficacy under variable climatic conditions, and large-scale validation of biocontrol and botanical agents. Coordinated efforts among researchers, extension agencies, and farmers are elemental for developing, refining, and adopting sustainable IDM modules for mungbean disease management.

Figure 1. Screening for Cercospora leaf spot disease resistance in mung bean

Figure 2. Cercospora leaf spot on mung bean

Plantix – The Farmer's Smart Companion in the Digital Age

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Abstract

PLANTIX is an innovative digital tool that helps farmers identify and manage crop-based problems with ease and accuracy. The app analyses images of selected plants affected by disease or pests using artificial intelligence to provide immediate diagnoses and practical solutions. It not only offers valuable information on disease identification but also provides features such as weather forecasts, fertiliser calculation, soil health updates, and nutrient management tips, thanks to its simple interface, multilingual support, and offline accessibility. It has become highly user-friendly and accessible to farmers across different regions. On the whole, it serves as a reliable companion for farmers, enabling them to make timely, informed decisions and to enhance the quality of their produce.

Introduction

The smart diagnosis app, PLANTIX, is an innovative mobile application designed to assist farmers mainly in identifying and managing crop diseases, pests, and nutrient deficiencies. It was developed by PEAT (Progressive Environmental and Agricultural Technologies) GmbH, a German startup based in Berlin. It is their flagship product, a digital agricultural advisor. It uses artificial intelligence to promote healthy and sustainable farming practices.

Some of its significant features are as follows: -

1)-Simple Interface: The app has a clean and easy-to-navigate design. It is so user-friendly that users with limited technical knowledge can operate it with ease.

One of the most extraordinary features of this app is its image-based diagnosis. Farmers simply need to click a picture of the affected plant part, and the app not only instantly identifies the problem by comparing it with its vast database, but also provides detailed information about the disease, possible causes, and customised practical treatment solutions. In addition, the app offers weather forecasts, crop health tips, and region-specific agricultural advice, helping farmers plan their activities more efficiently.

2)-Image-Based Diagnosis: Farmers only need to contribute a photo of the affected plants. The app quickly identifies the issue, removing the need for complex procedures or expert visits. It has a time and effort-saving mechanism.

3)-Multi-language Support: It is available in multiple local languages, allowing farmers from different regions to understand the information easily and apply it effectively.
4)-Offline Accessibility: Some of the features of the app can be used even without an active internet connection, thus making it helpful for farmers working in remote areas with poor network coverage.
5)-Step-by-Step Guidance: The app provides simple, straightforward, practical advice for managing plant diseases, pests, and nutrient deficiencies in a step-by-step manner.
6)-Weather and Soil Updates: It provides regular updates about weather conditions and soil health. Crop production technologies help farmers plan irrigation, sowing, and harvesting efficiently.

Fig. 1: Home Page

7)-Community Support: A built-in farmer community enables users and provides a platform to share experiences, ask questions, and get quick help from other growers and experts.
8)-Free and Accessible: It can be downloaded for free from app stores, ensuring that every farmer, regardless of income level, can benefit from its features.
9)- Scalability-It provides its services to millions of farmers globally by leveraging a data-driven ecosystem and robust technological infrastructure.
10)-Real-time disease tracker: The app tracks pest and disease outbreaks at a district level by using anonymised user data, which it uses to send real-time disease alerts to farmers.
The app's operating mechanism is straightforward yet highly effective. It uses advanced AI algorithms and machine learning models to analyse images uploaded by users. The data collected from millions of farmers worldwide continually improves its accuracy, creating an authentic, dynamic and evolving digital network of agricultural knowledge.

Conclusion

PLANTIX is an AI-Powered Crop Protection at farmers' fingertips that acts as a bridge between technology and farming. It empowers rural farmers to make better, timely decisions and increase productivity by providing timely, accurate, and location-specific guidance.

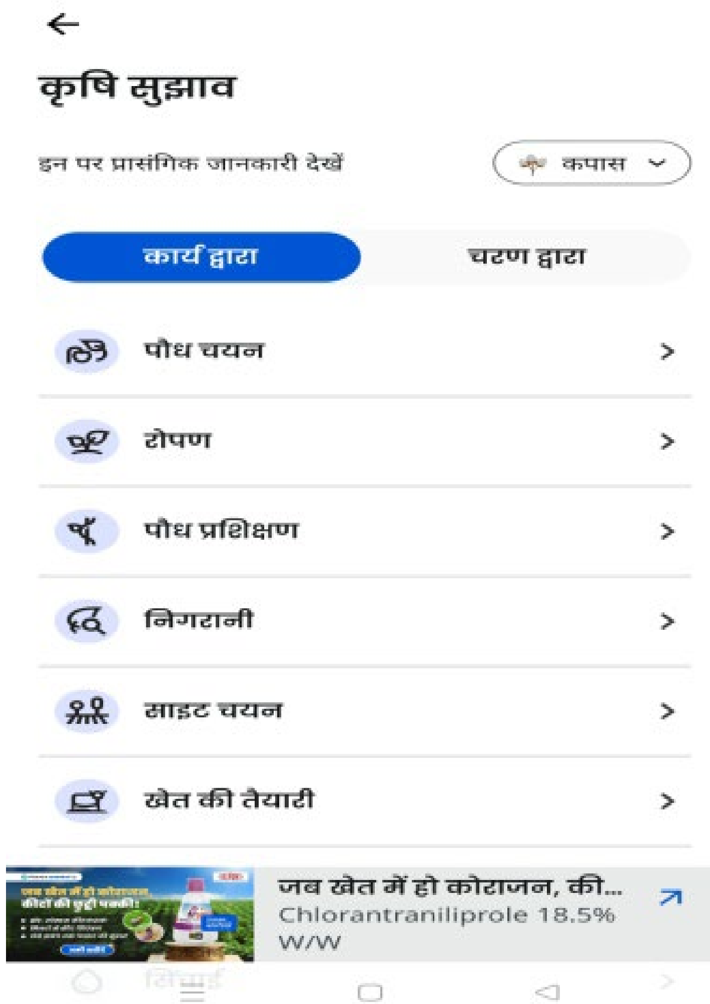

Fig. 2- Agricultural Information Page

Schemes to support agri-tourism for sustainable livelihoods in India

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Abstract

A significantly enhanced role of tourism in the Indian economy creates an enormous potential and opportunities for agro-tourism. Farm accommodation, farm catering, participatory agri-tourism, farm retailing, indigenous medico-support with farm entertainment etc are the Agro-tourism activities undertaken. The wide variety of scopes include farm stays, cultural and food parks, and an integrated model of crop and livestock with aesthetic values. The Government of India and various state governments have taken significant steps, including institutional, financial, social, and technical support, to encourage agro-tourism through multiple interventions, incentives, and schemes. Swadesh Darshan Scheme, PRASHAD Scheme, Scheme of Capacity Building for Service Providers (Institutes), and Marketing Development Assistance are implemented to provide institutional, financial and community management and engagement are noteworthy.

Keywords: Agrotourism. Scope, Incentives, schemes, benefits, livelihood

Introduction

The agriculture and Tourism sectors are driving forces for the Indian economy. Sustainable livelihood development, with farmers' socio-economic empowerment as the key agenda, is a central focus of India's development policy. Tourism plays a significant role in social, economic, cultural and environmental development. Beyond its financial contribution, tourism is increasingly recognised as a driver of inclusive development. The sector not only generates diverse employment opportunities, expected to exceed 48 million jobs in 2025 and nearly 64 million by 2035, but also contributes to cultural preservation, environmental sustainability, and international goodwill (***tourism.gov.in***). As more than 70 per cent of India's population depends on agriculture, directly or indirectly, and tourism is one of the most promising sectors, agri-tourism has immense potential. Agri-tourism can be a sustainable approach to the development of agriculture, as well as other sectors, such as cross-border tourism, inter-regional, community, and inter-country exchanges of culture and social values. This article helps to analyse the scope and benefits of various schemes implemented to boost tourism, especially agri-tourism, in the Indian context.

Concept of Agri tourism

Agri-Tourism generally refers to tourism activities that occur on farms and in their relevant context. It offers the opportunity to experience real-life situations in rural life and to get familiar with various farming tasks during a visit to a particular community or region. Agri-tourism can be defined in the following ways:

Agri-tourism is "the business of providing holidays for people on farms or in the countryside." Agri Tourism Development Cooperation, based in India, is defined as "the travel, which combines agriculture and rural setting with products of agricultural operations all within a tourism experience."

United Nations World Tourism Organisation (UNWTO, 1998) defines Agri tourism as "involving accommodation being offered in the farmhouse or in a separate guesthouse, providing meals and organising guests.

It is multifaceted and may entail agricultural tourism, agro tourism, farm tourism, farm vacation tourism, etc. Agri-tourism products and services can be divided into different types like farm accommodation, farm catering, participatory agri-tourism, farm retailing, therapy at the farm, holidaying on a farm and farm entertainment.

Scope of Agri Tourism in India

Agri-tourism in India, with various dimension emerge as a potential sector for agribusiness and commercial trading sectors, hence it has the following scope:

1. Widening Scope of Tourism due to its cost-effectiveness.
2. Curiosity about the rural and farming lifestyle: food, plants, animals, raw materials like wood, handicrafts, languages, culture, tradition, dresses and rural lifestyle.
3. Suitable for wholesome family-oriented activities, primarily recreational opportunities
4. Interest in natural environment, as a busy urban population can find leisure in a naturally beautiful environment, viz., birds, animals, crops, mountains, water bodies, etc.
5. Educational value of Agri-Tourism as it provides the best alternative for school picnics which are urban based and also hands on experience for urban college students in agriculture. (Karri, GN,)

Table 1: Scope of Agrotourism Activities

Sl No.	Agrotourism Farms	Types of Agrotourism Activities
1	Farm Stays	Farm House (Farm Home stays)
2	Day Farms	Farm tours, Farm restaurants,
3	Mixed cropping farms	Multiple cropping, indeginous farming system
4	Mixed Farming system farms	IFS model, ITK models , wadi
5	Horticultural Farms	Fruit, Flowers, Medicnal, aromatic garden
6	Livestock farm	Cattle, Buffalow
7	Hybrid farms	Crop garden +Mega food park +Tribal culture park

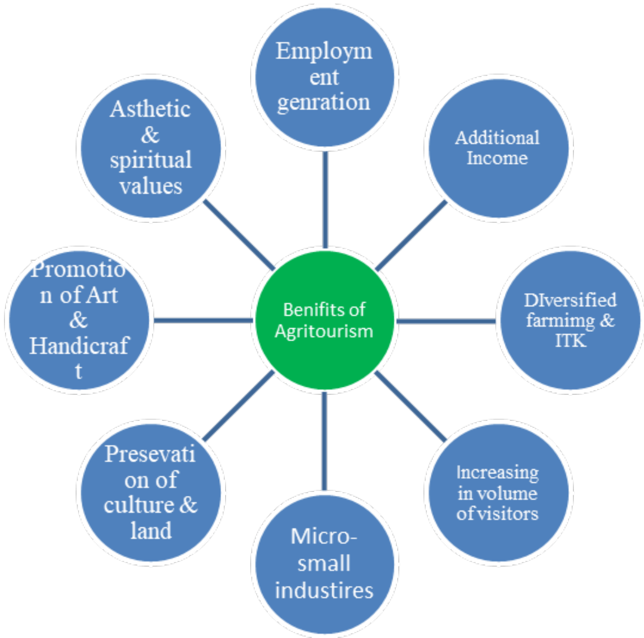

Fig.1: Benefits of Agri Tourism

Schemes to support Agri-tourism in India

Agri-tourism presents a unique opportunity to combine aspects of the tourism and agriculture industries to provide a number of financial, educational, and social benefits to tourists, producers, and communities. Government of India and state government provide various institutional, financial, social and technical supports to encourage agritourism by implementing different intervention, incentives and schemes. The following table highlighted key features with their potentialities related to agritourism of various interventions/schemes in India.

Table 2: **Schemes to support Agri-tourism in India**

Sl No.	**Schemes/ Intervention**	**Key Features**	**Agritourism potential**
1	Swadesh Darshan Scheme 2014	world-class infrastructure in the respective destination	❖ The scheme shall focus on providing funding support for development & renovation of Tribal Home stays and village community requirements. ❖ The endeavor will create community-based responsible tourism in the tribal villages of India through cultural exchange between tourists and indigenous people and create authentic tribal

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			rural experience for the tourists
2	PRASHAD Scheme 2014-15 'Pilgrimage Rejuvenation And Spiritual Augme	Focuses on identifying and developing the pilgrim sites across the country to enrich the religious tourism experience	❖ It also seeks to promote local art, culture, handicraft, cuisine, etc ❖ Assure active involvement of local communities through employment generation Create employment, specially for rural youth, like guiding, local hospitality, arranging services etc. ❖ Development of small scale enterprises in nearby area based on local resources like apple, wood, medicines etc.
3	Scheme of Capacity Building for Service Providers (Institutes)	Under this scheme the institutions are conducting Training using their own infrastructures in their own premises or are providing the training at site of the service providers.	❖ A large number of the Service providers are located around the tourist sites and therefore such persons have to be trained at their place of work ❖ unorganized sector such as rural tourism are given some inputs so as to upgrade their behavior and service skills.
4	Marketing Development Assistance	Financial support will be provided to tourism service providers	❖ Participation in travel fairs/exhibitions and road shows (organized by Ministry of Tourism) ❖ activities such as roadside stands, farm tours, bed-breakfast, and cattle drives

Conclusion:

Government takes various steps to create tourism sector more visualize in rural area. Agri-tourism is act as driving force to achieve the vision of Vikasit Bharat. Agri-tourism involves any agriculturally based activity that brings visitors to a farm which includes various activities of farming and also acts as additional source of income, enjoyment, entertainment etc.

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Plant Physiology: Core Processes and Their Applications in Agriculture

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Abstract

Plant physiology explains the fundamental biological processes that govern plant growth, development, and productivity. Key physiological functions such as photosynthesis, transpiration, respiration, nutrient uptake, growth regulation, and stress responses directly influence crop performance under diverse agro-climatic conditions. An understanding of these processes enables efficient management of water, nutrients, and environmental stresses, thereby improving yield and resource-use efficiency. Integration of plant physiological principles with modern agricultural practices is essential for developing sustainable, climate-resilient, and high-productivity cropping systems.

Introduction

Plant productivity and agricultural sustainability are fundamentally governed by physiological processes that regulate growth, development, and environmental adaptation. As plants are immobile, they rely on highly coordinated internal mechanisms to manage water relations, nutrient acquisition, energy production, and stress tolerance under changing climatic and edaphic conditions. An understanding of plant physiology, therefore, provides the scientific basis for improving crop performance and ensuring food security.

Core physiological processes such as photosynthesis, transpiration, respiration, and nutrient uptake determine the efficiency with which plants convert natural resources into biomass and economic yield. These processes are further regulated by plant growth regulators, source–sink relationships, and environmental signals. Any disruption in these physiological functions—due to nutrient imbalance, water stress, or extreme temperatures—directly affects crop growth and productivity.

In modern agriculture, applying plant physiological principles has become increasingly crucial for optimising resource use, enhancing stress resilience, and sustaining yields amid climate variability. This article discusses the major physiological processes in plants and highlights their practical applications in agriculture, emphasising their role in achieving sustainable and climate-resilient crop production systems.

1. Water Relations and Transpiration

Water relations govern cell turgidity, nutrient transport, and physiological activity in plants. Absorption of water by roots occurs through osmotic and active processes, while transpiration generates a pulling force for upward water movement. Stomatal regulation maintains the balance between water loss and CO_2 uptake.

Agricultural applications:

Efficient irrigation scheduling is based on plant water relations to avoid drought

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stress and wilting. Understanding transpiration helps in adopting practices such as mulching, drip irrigation, and antitranspirant use to improve water-use efficiency. Crop varieties with better stomatal regulation and deeper root systems are preferred in water-scarce regions.

2. Mineral Nutrition and Nutrient Uptake

Plants require essential nutrients for structural, metabolic, and enzymatic functions. Nutrient absorption occurs through root membranes using active transport and diffusion. Nutrient deficiency or toxicity leads to physiological disorders that affect growth and yield.

Agricultural applications:

Knowledge of nutrient uptake helps in precise fertiliser application and integrated nutrient management (INM). Soil testing, fertigation, and foliar feeding are based on physiological nutrient requirements. Correcting nutrient deficiencies improves crop health, yield, and quality.

3. Photosynthesis and Crop Productivity

Photosynthesis is the process by which plants convert solar energy into chemical energy stored in carbohydrates. The rate of photosynthesis depends on light, CO_2 concentration, temperature, and water availability. Photosynthetic efficiency directly determines biomass accumulation and yield.

Agricultural applications:

Crop spacing, canopy management, and weed control are designed to maximize light interception. C_4 crops like maize and sorghum are promoted in hot climates due to higher photosynthetic efficiency. Breeding programs focus on improving photosynthetic traits to increase yield potential.

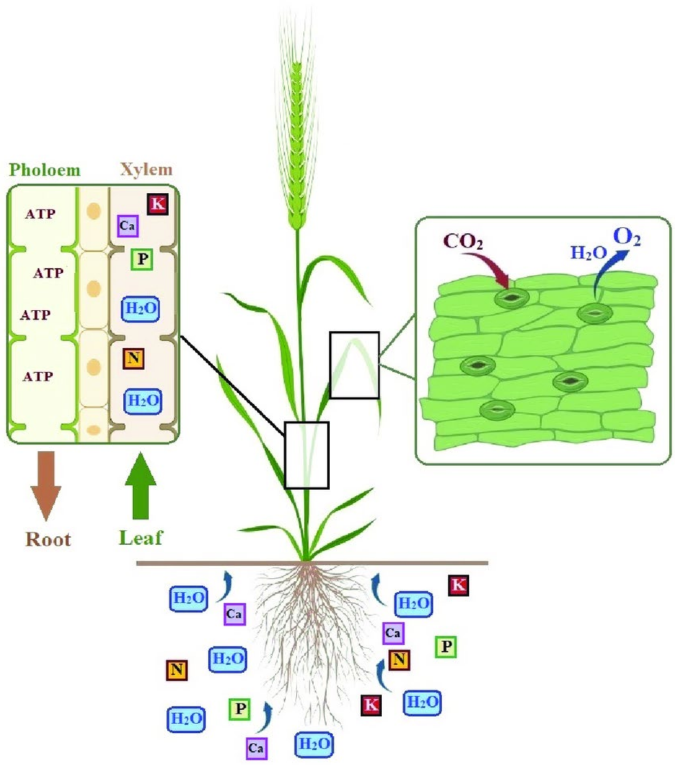

Figure 1: Integrated plant physiological processes showing root uptake of water and nutrients, xylem–phloem transport, stomatal gas exchange, and their collective role in supporting plant growth and productivity.

4. Respiration and Energy Utilisation

Respiration supplies the energy required for growth, maintenance, and metabolic activities. It involves the breakdown of carbohydrates through glycolysis, the Krebs cycle, and oxidative phosphorylation. Excessive respiration can reduce net productivity.

Agricultural applications:

Post-harvest storage practices aim to reduce respiration rates to extend shelf life of fruits and vegetables. Temperature and oxygen control in storage facilities minimize respiratory losses. Crop management practices that balance

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photosynthesis and respiration improve yield efficiency.

5. Translocation of Photosynthates

Photosynthates produced in leaves are translocated to growing and storage organs through the phloem. Source–sink relationships regulate the allocation of carbohydrates to roots, fruits, and seeds.

Agricultural applications:

Understanding translocation helps in improving grain filling, fruit development, and tuber formation. Practices such as pruning, thinning, and balanced fertilisation help optimise the source–sink balance. Yield improvement strategies focus on enhancing sink strength in economic plant parts.

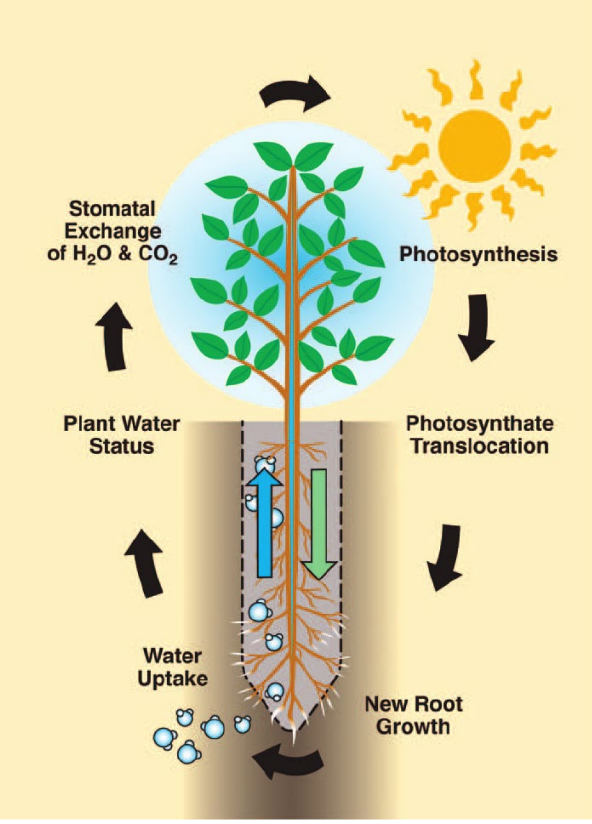

Figure 2: Physiological integration of water uptake, stomatal regulation, photosynthesis, and photosynthate translocation governing plant water status, growth, and development.

6. Plant Growth Regulators and Crop Management

Plant hormones regulate cell division, elongation, flowering, fruiting, and senescence. Auxins, gibberellins, cytokinins, ethylene, and abscisic acid act in coordination to control growth and development.

Agricultural applications:

Growth regulators are widely used to improve crop performance—auxins for rooting, gibberellins for fruit size, cytokinins for delayed senescence, and ethylene for fruit ripening. Hormonal manipulation increases crop yield, uniformity, and market quality.

7. Seed Germination and Dormancy

Germination involves the activation of metabolic processes that lead to seedling establishment. Dormancy prevents germination under unfavourable conditions and is regulated by hormonal balance and environmental cues.

Agricultural applications:

Breaking dormancy ensures uniform germination and crop stand establishment. Seed priming, scarification, and chemical treatments improve germination percentage. Understanding germination physiology is crucial for seed technology and nursery management.

8. Stress Physiology and Crop Adaptation

Plants experience abiotic stresses such as drought, salinity, heat, and cold, which disrupt physiological processes. Stress tolerance involves osmotic adjustment, antioxidant activity, and hormonal signaling.

Agricultural applications:

Stress physiology guides the development of crop varieties that are tolerant and climate-resilient farming systems. Practices such as stress hardening, use of osmoprotectants, and selection of tolerant cultivars reduce yield losses. Stress management strategies are vital in the context of climate change.

9. Plant–Environment Interaction

Plant growth is influenced by environmental factors such as light, temperature, water, and soil conditions. Physiological responses enable plants to adapt to varying agro-climatic zones.

Agricultural applications:

Crop selection and cropping systems are designed based on physiological adaptability. Protected cultivation modifies environmental factors to enhance physiological efficiency. Agroforestry and crop diversification leverage plant–environment interactions to sustain production.

Conclusion

Plant physiology provides the scientific foundation for modern agriculture by explaining how plants grow, develop, and respond to environmental conditions. Applying physiological principles enables efficient resource use, higher productivity, and improved stress tolerance. Integration of plant physiology with agronomic practices is essential for sustainable and climate-resilient agriculture.

Visual Intelligence in Precise Detection of Plant Diseases in Agriculture

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Abstract

Agriculture, the foundation of global food security, is increasingly threatened by the rapid rise of plant diseases, challenges that traditional detection methods struggle to manage effectively across vast farmlands and remote regions. Visual Intelligence (VI), an advanced integration of AI, computer vision, and deep learning models such as Vision Transformers (ViT), GreenViT, and PMVT, is revolutionizing plant disease diagnosis by offering unmatched accuracy, speed, and scalability. Unlike conventional CNNs, ViTs excel at capturing both global context and subtle spatial patterns, enabling early and dependable detection of complex diseases across diverse crops and environments. Practical implementations through drones, edge devices, and mobile applications highlight VI's ability to provide real-time, affordable, and offline disease monitoring directly to farmers. With its growing role in precision spraying, IoT-enabled field monitoring, and smartphone-based diagnostics, VI helps reduce crop losses, minimize chemical usage, and promote sustainable farming. Despite ongoing challenges related to computational demands, data limitations, explainability, and environmental variability, rapid advancements such as multi modal imaging, explainable AI, richer datasets, and highly efficient edge models are positioning VI as a critical tool for building climate resilient and future ready agricultural systems.

Keywords: Visual intelligence, plant diseases, agriculture

Introduction

Agriculture is the backbone of many global economies, contributing significantly to food security and livelihood. According to the World Bank report of 2018, agriculture engaged over a billion people, representing 28.5% of the total labour force, and amounted to about 10 million tons of food production daily. But, as plant diseases continue to rise, they pose serious threats to crop yields and food security. Major food crops such as rice, wheat, potatoes, soybeans, and maize can suffer losses of 10 to 40% due to plant pathogens, with transboundary plant diseases increasing significantly due to globalization, trade, climate change, and agricultural intensification.

Traditional methods of detecting plant diseases—mainly through expert visual inspections—are time-consuming, labor-intensive, and often ineffective, especially in large-scale farming operations or remote rural areas where trained personnel are usually not available. The quality of diagnosis depends heavily on the knowledge of human experts, which is not easily acquired by agricultural sector and is less accessible, particularly for small farms in developing countries. This expertise gap becomes even more critical when dealing with diseases that exhibit subtle early symptoms or those requiring differentiation between visually similar infections. Consequently, this leads to the urgent need for smarter, automated solutions that are scalable, reliable, and accessible to farmers regardless of their location or technical expertise.

That's where **Visual Intelligence (VI)** comes in—a transformative technology that is revolutionizing agricultural disease management. VI represents a sophisticated blend of computer vision, artificial intelligence (AI), and deep learning techniques that enable machines to understand and interpret plant images with remarkable accuracy. One of the most exciting and recent developments in this area is the **Vision Transformer (ViT)** model, which offers a more accurate, efficient, and robust approach to detect plant diseases compared to traditional Convolutional Neural Network (CNN)-based methods.

Understanding Visual Intelligence and Why It matters in Agriculture

Visual Intelligence is a machine's ability to "see" and make sense of visual information—like spotting disease symptoms on a leaf. This capability is being used to detect diseases early, monitor plant growth, and support modern, data-driven farming practices.

Traditionally, image analysis in agriculture has relied on **Convolutional Neural Networks (CNNs)**. While powerful, CNNs have two major limitations:

1. **Loss of spatial information**: CNNs often lose important spatial details because of pooling operations used for dimensionality reduction, which results in the loss of vital information including the precise location of the most prominent disease features.
2. **Local focus limitation**: They primarily focus on local patterns within limited receptive fields but can miss the broader contextual relationships across the entire image, potentially overlooking subtle disease patterns that manifest across larger leaf areas.
3. **Translation invariance issues**: CNNs' inherent translation invariance can sometimes be a disadvantage when the exact location and spatial arrangement of disease symptoms are critical for accurate diagnosis.

To address this, researchers developed **Vision Transformers (ViTs)**, inspired by models originally built for processing language. Instead of analyzing images as a whole, ViTs break them down into smaller patches and then process these patches in parallel. This allows the model to capture relationships across the entire image.

With reference to plant disease detection, models like **GreenViT** demonstrate this innovative approach effectively. The GreenViT model divides an input image (typically 224×224 pixels) into equal-sized patches (e.g., 16×16 pixels each), encodes each patch with positional information to maintain spatial relationships, and runs them through transformer encoder blocks. This patch-based process, combined with multi-head self-attention mechanisms, helps the system to recognise subtle patterns such as the precise distribution and arrangement of rust spots on a wheat leaf or the characteristic yellowing patterns in virus-infected tomato plants, making it considerably easier to differentiate one disease from another, even when symptoms appear superficially similar.

Furthermore, ViT-based models can effectively capture long-range dependencies among different parts of a leaf, which is particularly valuable when disease symptoms manifest across spatially separated regions. For instance, bacterial spot diseases often present as scattered lesions across the leaf surface, and understanding the relationship among these dispersed symptoms is crucial for accurate diagnosis.

Thus, Visual Intelligence, powered by Vision Transformers, is revolutionising plant pathology by offering a more accurate, scalable, context-aware, and faster disease detection tool compared to traditional CNN-based methods and manual inspection approaches.

Applications of Visual Intelligence in Precision Agriculture

Visual Intelligence, primarily through ViTs, is reshaping how we approach agriculture in the following way-

1. **Disease Detection:** Models like **GreenViT** and **PMVT** accurately detect plant diseases from images, even across different crop types and environmental conditions.
2. **Edge Device Deployment:** These lightweight models can run on low-power devices like **Raspberry Pi**, enabling real-time, offline disease diagnosis in rural areas.
3. **Smart Spraying with Drones:** Drones equipped with AI can detect infected plants and apply pesticides only where needed, reducing chemical usage and cost.
4. **Mobile Apps for Farmers:** Farmers can snap a photo of a plant using smartphone apps that use models like PMVT to provide instant disease identification.
5. **IoT-Driven Field Monitoring:** When combined with sensors and drones, VI models support continuous, large-scale monitoring of plant health.

These applications help make farming more precise, efficient, and environmentally sustainable.

Case Studies and Practical Examples

Case Study 1: GreenViT for Multi-Crop Disease Detection

Research Context: Researchers developed GreenViT, a fine-tuned Vision Transformer model specifically optimised for plant disease detection, addressing the computational constraints often encountered in agricultural settings.

Methodology: The GreenViT architecture was based on the ViT-Base model but significantly optimised by reducing the number of encoder layers from 12 to 8, decreasing attention heads from 12 to 4, and utilising smaller input image dimensions (72×72 pixels compared to the standard 224×224). This fine-tuning successfully reduced the total number of learning parameters from 86 million to 21.65 million without compromising accuracy, a critical achievement for deployment on resource-limited devices.

Datasets and Training: The model was trained and evaluated on three comprehensive datasets:

- PlantVillage (PV): 54,305 images from 14 plant species categorised into 38 classes (26 diseased, 12 healthy)
- Data Repository of Leaf Images (DRLI): 4,502 images from 12 plant species (guava, arjun, mango, alstonia, bael, jatropha, jamun,

pomegranate, basil, lemon) captured in natural field environments

- Plant Composite (PC): A merged dataset of 58,807 images created to test robustness and generalization

Significant Outcomes:

- Outstanding Accuracy: GreenViT achieved 100% accuracy on PlantVillage (top-1 accuracy on test set of 10,495 images), 98% on DRLI, and 99% on the Plant Composite dataset, substantially outperforming baseline CNN models including VGG19 (99% on PV, 97% on DRLI), VGG16 (100%, 96%), and even the original ViT-Base model (95%, 75%).
- Cross-Validation Robustness: The model demonstrated exceptional consistency with 5-fold cross-validation, yielding average test accuracies of 97.52% (PV), 94.46% (DRLI), and 95.40% (PC), and 10-fold cross-validation, achieving 97.40%, 94.45%, and 95.79%, respectively, confirming reliable performance across different data splits.
- Low False Alarm Rate: GreenViT exhibited the lowest False Alarm Rate (FAR) among all compared models, which is crucial for practical deployment as it minimises unnecessary interventions and treatment costs.
- Real-World Deployment: The model was successfully implemented on Raspberry Pi 4B (quad-core Cortex-A72 processor with 4GB RAM), achieving 0.34 FPS on this edge device and 22.19 FPS on standard CPUs, making it viable for field deployment in resource-constrained agricultural environments.

Practical Implications: This case study demonstrates that carefully optimized ViT models can achieve state-of-the-art accuracy while remaining computationally efficient enough for deployment on affordable edge devices commonly available to farmers and agricultural extension workers, bridging the gap between cutting-edge AI research and practical agricultural applications.

Case Study 2: PMVT (Plant-based MobileViT) for Mobile Device Deployment

Research Context: Researchers developed PMVT to address the dual challenge of achieving high accuracy while maintaining extreme computational efficiency suitable for mobile devices with limited processing power, storage capacity, and energy supply.

Architectural Innovation: PMVT introduced several key innovations:

- **Inverted Residual Blocks with 7×7 Convolutions**: Replaced the standard 3×3 convolution kernels with larger 7×7 kernels to effectively model long-distance dependencies between different leaves in plant disease images, handy for detecting patterns across crisscrossing leaves.
- **Convolutional Block Attention Module (CBAM) Integration**: Integrated both channel attention and spatial attention mechanisms into the standard ViT encoder, allowing the network to dynamically adjust feature weights and focus on disease-relevant regions while suppressing irrelevant background information.

- **Three Model Variants**: Created three versions—PMVT-XXS (0.98M parameters), PMVT-XS (2.01M parameters), and PMVT-S (5.06M parameters)—to accommodate different resource constraints.

Experimental Validation: The model was rigorously tested on three diverse agricultural datasets representing different real-world challenges:

Wheat Dataset (Lian, 2022): 4,087 images depicting seven wheat disease categories, captured with real-world environmental interference (sky, soil, weeds).

- **PMVT-XXS Achievement**: 93.6% accuracy with only 0.98M parameters, outperforming MobileNetV3-Small (92.0% with 1.54M parameters) by 1.6%
- **PMVT-XS Achievement**: 94.7% accuracy, surpassing EfficientNet-B0 (94.1% with 4.03M parameters) while using only half the parameters
- **PMVT-S Achievement**: 94.9% accuracy, significantly outperforming ResNet-101 (94.1% with 42.5M parameters) while using 8.4× fewer parameters

Coffee Dataset (Parraga-Alava et al., 2019): 1,000 selected images from natural field environments with complex backgrounds including healthy leaves, red spider mite infestations, and rust disease.

- **PMVT-XXS**: 85.4% accuracy under same parameters as SqueezeNet-1.1 (83.1%), achieving 2.3% improvement
- **PMVT-XS**: 86.5% accuracy, outperforming MobileFormer-96M (84.2%) by 2.3%
- **PMVT-S**: 87.6% accuracy, surpassing PoolFormer-S12 (85.4%) by 2.2%

Rice Dataset (Sethy, 2020): Binary classification problem (healthy vs. unhealthy) tested in both controlled laboratory and real field conditions.

- **PMVT-XS Outstanding Performance**: 97.7% accuracy, dramatically exceeding MobileNetV3-Large (91.9%) by 5.8%
- **PMVT-XXS**: 93.1% accuracy, outperforming MobileNetV3-Small (89.7%) by 3.4%

Significant Outcomes:

- **Superior Parameter Efficiency**: PMVT consistently achieved higher accuracy with fewer parameters compared to both lightweight networks (MobileNet variants, SqueezeNet, ShuffleNet) and heavyweight networks (ResNet, VGG, EfficientNet).
- **Ablation Study Insights**: Component-wise analysis revealed that both the 7×7 convolution kernels and CBAM modules independently contributed to improved accuracy, with their combination yielding the best results. For example, on the wheat dataset, the baseline MobileViT-XXS achieved 91.4%, adding 7×7 convolutions improved it to 92.2%, adding CBAM alone improved it to 92.5%, and combining both (PMVT-XXS) achieved 93.6%.
- **Cross-Validation Consistency**: 5-fold and 10-fold cross-validation demonstrated stable performance across different data splits, with average test accuracies remaining

competitive even when training samples per fold were reduced.

- **Practical Mobile Application**: The research team developed and deployed a fully functional Android application with features including camera-based real-time identification, gallery image selection, disease database search, and comprehensive result display with treatment recommendations—all processing performed locally on the device.

Practical Implications: This case study establishes that hybrid CNN-ViT architectures with attention mechanisms can achieve exceptional accuracy-efficiency trade-offs, making sophisticated AI-powered disease diagnosis accessible to farmers worldwide through ubiquitous smartphone devices, without requiring internet connectivity or cloud computing resources.

Other Notable Deployments

- **Drones + ViT Models**: Used to detect and spray only infected crop areas.
- **Tomato & Apple Leaf Detection**: While traditional CNNs hit 70–90% accuracy, ViTs crossed the **95%** mark.

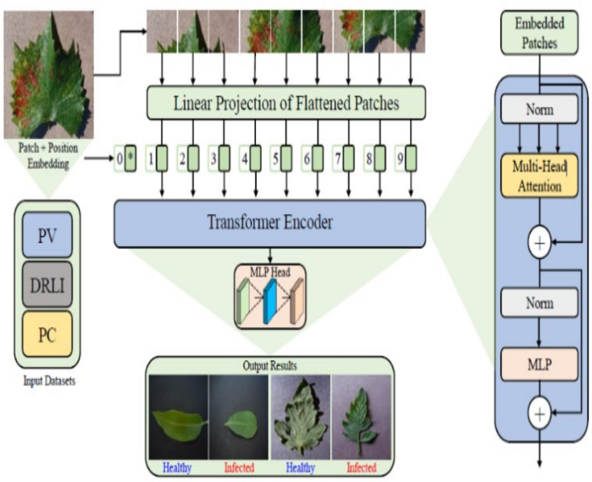

Fig 1. An overview of the proposed GreenViT framework for diagnosing plant diseases
Source: https://doi.org/10.3390/s23156949

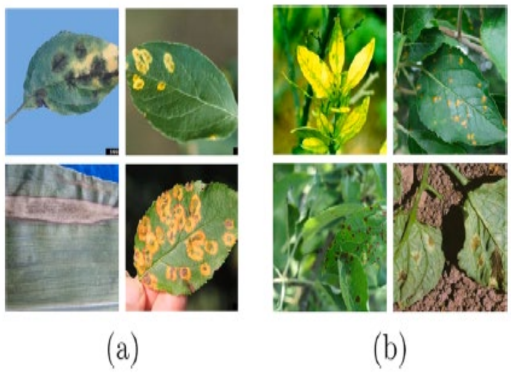

Fig. 2. Examples of the (a) IPM and (b) Bing images
Source: https://doi.org/10.1016/j.compag.2020.105220

Integration of Visual Intelligence and field

Bringing Visual Intelligence into the field in general terms refers to combining software smarts with physical tools:

- **On-Device AI (Edge AI):** Models like PMVT can run on devices such as **Jetson Nano**, **Raspberry Pi**, or smartphones, making offline diagnosis possible even without internet.
- **Drones for Precision Tasks:** Drones with cameras capture field images. These are analyzed by onboard or cloud-based ViTs, and drones can act instantly—by spraying or sending alerts.
- **IoT and Cloud Integration:** Combining sensor data (temperature, humidity) with visual inputs helps create more robust and responsive disease prediction systems.
- **Apps for Farmers:** With user-friendly mobile apps, even farmers in remote regions can get accurate diagnoses by just taking a picture.

Benefits of Visual Intelligence in Agriculture

- **Early Detection**: Spot diseases before they spread.
- **Greater Accuracy**: ViTs outperform CNNs by understanding both local and global patterns.
- **Cost Savings**: Less need for expert intervention, more targeted pesticide use.
- **Eco-Friendly**: Reduces chemical use by treating only infected zones.
- **Flexible Use**: Works for small farms, large estates, greenhouses, and open fields.

Future Directions

Multi-Modal AI Integration

Future VI systems will integrate multiple complementary data modalities to enhance diagnostic accuracy and early detection capabilities. Hyperspectral and multispectral imaging can detect subtle biochemical changes in plant tissues through chlorophyll fluorescence patterns and altered spectral signatures days before visual symptoms appear, enabling early-stage infection identification and differentiation between abiotic stress and biotic diseases. Thermal imaging detects temperature variations associated with disrupted transpiration in diseased tissues, distinguishing water stress from disease-induced wilting and identifying vascular diseases. Incorporating real-time environmental data (temperature, humidity, rainfall, soil characteristics) enables risk assessment based on conditions favoring specific pathogens and predictive modeling of disease progression. Integrating crop variety information and known resistance gene profiles improves diagnostic accuracy by considering host pathogen compatibility and guides variety selection for disease management. The primary research challenge lies in developing unified deep learning architectures capable of effectively fusing heterogeneous data types while maintaining computational efficiency for edge deployment.

Explainable AI (XAI) for Agricultural Applications

While achieving high accuracy, current VI models function as "black boxes," creating trust barriers for agricultural practitioners. Enhanced visualization techniques will provide multi-scale attention visualization showing which features at cellular, tissue, organ, and whole-plant levels contribute to diagnosis, temporal symptom progression tracking explaining how symptom evolution influenced identification, and comparative visual explanations displaying why samples were diagnosed as one disease rather than alternatives. Feature attribution methods (SHAP, LIME, GradCAM++) will quantify contributions of specific symptoms to predictions and reveal potential model biases. Counterfactual explanations through "what-if" scenarios help users understand diagnostic boundaries. User-centered design will tailor explanation interfaces to different stakeholders—simple visual explanations for farmers, detailed explanations with differential diagnosis for extension agents, and comprehensive technical explanations for researchers. Critical research priorities include creating standardized XAI evaluation frameworks for agricultural domains and developing computationally efficient XAI methods suitable for edge devices.

Diverse and Representative Datasets

Existing datasets like PlantVillage, captured under controlled laboratory conditions, poorly represent real-world agricultural complexity, causing 40-50% performance drops when deployed on field images. Addressing this gap requires building large-scale field-collected datasets containing hundreds of thousands of images from diverse geographic regions, crop varieties, management practices, disease severity levels, and mixed infections. Temporal disease progression series tracking individual plants from infection through symptom development enables models to learn disease dynamics and improve early detection. Expert-verified annotations with laboratory diagnostic confirmation for disease identity, comprehensive metadata on environmental conditions and crop history, and focused collection efforts for rare, emerging, and orphan crop diseases are essential. Datasets must include comprehensive negative examples (healthy tissues, abiotic disorders, pest damage, senescence) to reduce false positives. Data sharing infrastructure including centralized repositories, privacy-protecting agreements, and automated quality control mechanisms for crowd-sourced data are critical. Developing simulation and augmentation techniques preserving realistic field variability while expanding dataset diversity remains a priority.

Improved Edge Device Performance

Achieving real-time inference on resource-constrained devices requires multiple optimization approaches. Hardware acceleration through specialized neural processing units (NPUs) like Google's Edge TPU and Apple's Neural Engine will reduce inference latency by 10-100× compared to CPUs and enable >30 FPS on mobile devices. Mixed-precision quantization using different bit-widths for different layers (16-bit for attention, 8-bit for less sensitive layers) achieves 4-8× speedup with <1% accuracy loss. Neural Architecture Search (NAS) for agriculture automates discovery of optimal lightweight architecture specifically for plant disease detection. Knowledge distillation techniques train compact "student" models matching larger "teacher" model performance. Sparse attention mechanisms reduce computational complexity from $O(n^2)$ to $O(n \log n)$ through local attention windows and learned sparsity patterns. On-device continual learning enables models to adapt to local disease patterns, incorporate user corrections, and update with new disease categories without cloud connectivity. Research priorities include developing standardized agricultural-specific edge AI benchmarks, creating open-source optimized model libraries for common platforms, and establishing hardware-software co-design methodologies.

Climate Change Adaptation and Resilience

Climate change fundamentally alters disease landscapes by expanding pathogen geographic ranges, extending growing seasons allowing multiple disease cycles annually, creating novel conditions favoring different pathogen combinations, and increasing extreme weather events stressing plants. VI systems must develop rapid model updating capabilities to incorporate newly arrived pathogens and novel symptom expressions. Climate-disease relationship modeling should integrate long-term climate projections with disease forecast models, incorporate historical disease-climate correlations, account for extreme weather impacts, and predict geographic range shifts for important pathogens. Adaptive management recommendations should guide varietal selections anticipating future disease pressures, modify cultural practices for changing conditions, plan infrastructure investments considering future challenges, and diversify cropping systems for resilience. Research priorities include developing VI systems with built-in adaptability to changing disease landscapes, creating partnerships between AI researchers and climate scientists to integrate climate projections, and establishing sentinel monitoring networks for early detection of disease range expansions and novel emergence.

Challenges to Overcome

Despite all its promise, there are still some hurdles:

1. **Heavy Computation Needs**: ViTs can be resource-intensive, especially on low-power devices.
2. **Data Limitations**: Many datasets (like PlantVillage) are lab-based and don't fully represent real-world conditions.
3. **Generalization Issues**: Some models may not perform well across different crops or environments.
4. **Black Box Problem**: It's hard to explain exactly why a model made a certain decision.
5. **Field Conditions**: Lighting, background clutter, or overlapping symptoms can reduce accuracy. Overcoming these will be key to making Visual Intelligence a mainstream agricultural tool.

Conclusion

Visual Intelligence, powered by models like **GreenViT** and **PMVT**, is changing how we approach agriculture. It is making disease detection faster, more accurate, and accessible even in areas without expert help. These models can work in drones, mobile apps, and IoT systems, empowering farmers to make informed decisions in real time. While technical and practical challenges still exist, continuous innovation is pushing the boundaries. With smarter models, better datasets, and easier-to-use tools, VI is well on its way to becoming a core part of sustainable and resilient agriculture.

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Table 1. Quantitative basis for the scale and robustness of the model.
(Source : https://doi.org/10.3390/s23156949)

S. No.	Dataset	Training	Testing	Validation	Total Images
1	PlantVillage [13]	39,100	10,861	4344	54,305
2	Data Repository of Leaf Images [14]	3241	901	360	4502
3	Plant Composite [39]	42,341	11,762	4704	58,807

Makhana Cultivation: A Profitable and Sustainable Aquatic Crop for Indian Farmers

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Abstract

Makhana (*Euryale ferox* Salisbury), commonly known as fox nut or gorgon nut, is an important traditional aquatic non-cereal crop of India with high nutritional, medicinal, and economic value. It is organically cultivated in waterlogged areas, particularly in North Bihar, Assam, and parts of Bengal, with Bihar contributing about 90% of India's production. Rich in carbohydrates, protein, minerals, and energy, makhana is considered a superior dry fruit and is widely used in foods and traditional medicine. Cultivation is mainly practised through pond and field systems, with the field system offering higher productivity and better crop management. Makhana farming provides sustainable livelihoods for small and marginal farmers, especially the Mallah community, and holds strong potential to generate income and drive export growth.

Introduction

Makhana is one of the traditional foods of India, also known as Foxnut, Gorgon nut, and black diamond, and is obtained from the seeds of the Prickly water lily **(Sundaram et al. 2014).** Makhana is a unique, highly nutritious, fully organic non-cereal food, a blessing for the rural poor, especially in the flood-prone zones of north Bihar, lower Assam, and parts of Bengal, who have perfected the art of cultivating fox nut. It is a unique, prickly macrophyte typically found in the littoral zones of waterlogged areas, ponds, and low-lying areas. Scientifically, it is known as Euryale ferox Salisbury, which belongs to the Family Nymphaeaceae and is native to Southeast Asia and China. It is the first aquatic non-cereal cash crop in Bihar. Bihar accounts for 90 per cent of India's Makhana production and approximately 85 per cent of the global output **(Singh and Agrawal 2024).** The Kosi and Mithilanchal Regions, including these districts (Supaul, Saharsa, Madhubani, Darbhanga, Madhepura, Purnea, Katihar, Araria, Sitamarhi, Kishanganj) are a dominant zone for makhana cultivation due to their waterlogged condition and traditional knowledge System **(Sonu and Jha 2025).** In the M.P. Four districts (Narmadapuram, Balaghat, Chhindwara, Seoni), the Makhana farming has been initiated through a pilot project. The seeds of Makhana are popped and eaten roasted, as well as used in the preparation of various kinds of sweets and recipes. Makhana is considered a superior dry fruit, as it is rich in several essential nutrients. As a dietary property, the raw makhana contains 76.9% carbohydrates, 12.8% moisture, 9.7% protein, 0.9% phosphorus, 0.5% minerals, 0.1% fat, 0.02% calcium and 0.0014% iron. In popped makhana, 84.9% carbohydrate, 4% moisture, 9.5% protein, and 0.5% fat **(Sah et al.,**

2013). The calorific value of seeds is 362 Kcal/100g in their raw state, compared with 328 Kcal/100g in their popped state. As for medicinal properties, makhana is recommended for the treatment of diseases of the respiratory, circulatory, digestive, excretory, and reproductive systems **(Qudrat et al., 2000).** The edible seed is known for its tonic, astringent, deobstruent, antirheumatic, antidiuretic and roborant properties. Makhana is used as a tonic and for the treatment of leucorrhoea, and is also a good immunostimulant **(Puri et al., 2000).**

Cultivation

Makhana is an obligate self-pollinated, seed-propagated plant, cultivated in tropical and subtropical climates. For proper growth and development, the conducive range of air temperature is 20°C-35°C, relative humidity 50%-90%, and annual rainfall 100-250 cm, and the water bodies should be organically reached, with less than 50% water transparency **(Mandal et al., 2010).** Makhana is generally sown in December and harvested in the Morning hours in August. It is ideally cultivated in stagnant perennial water bodies like ponds, land depressions, oxbow lakes, swamps and ditches by two systems:-

1. Pond System:- Pond system of cultivation is one of the oldest and traditional methods of fox nut cultivation used by makhana growers in different parts of India. This system is very tedious, labour-intensive and time-consuming in weed management. It takes a duration of 8 to 10 months; thus, no other crop can be grown. The primary source of water in the pond system is natural water. In this system the requirement of seed for new ponds and water is 80-90 Kg/ha and up to 4-6 feet water level during the crop duration. In this system, sowing makhana seed directly in newly created water bodies is required. In contrast, in the old pond, which has already been harvested, sowing is not needed, as leftover seed serves as planting material for the next crop. The yield remains low, 1.8 to 2.0 ton/ha. The Pond system is linked to low productivity, as collecting seed from the bottom is a very tedious process and a drudgery for Jalkar farmers.

Figure 1: Pond system

2. Field System:- Field system is straightforward to operate and provides opportunities to cultivate cereals and fodder crops like rice, berseem, wheat in the same piece of land in the same year. In this system, makhana is grown using the transplanting method, and the crop lasts 4-5 months. The primary source of water in the field system is irrigation water, which must maintain a minimum 1-foot level throughout the crop season. In the field system, sowing of the crops in the nursery in December. 20 kg of healthy seed is broadcast uniformly across the entire nursery plot. For transplanting in a 1-hectare area, 500 m2 is enough for raising the nursery. A water level of 0.30 m is maintained throughout the seedling growing period, i.e., from December to March. The seedlings are transferred from the nursery plot to the main field in the first week of April and transplanted at a distance of 1.20 x 1.25. Field cultivation requires the adoption of fertilisers such as NPK and urea and scientific crop management practices.

Figure 2: Field system

This system allows for better weed management, significantly reducing labour requirements and costs. The expected yield of makhana through this system is 2.6 to 3 tons/ha.

Harvesting

Traditional methods still involve harvesting the seed. The ripe fruits burst in July-August, and the ripened seeds settle at the bottom of the pond within 2-3 days. Collection of seeds from the pond bottom begins in August and is a very tedious job performed only by skilled professionals. Collected seeds are thoroughly thrashed by feet to remove the membranous cover. Makhana is harvested from 6 a.m. to 11 a.m., and the drudgery is done in the morning in August to October. The fishermen community (Mallah), belonging to the weaker sections of society, is mainly involved in makhana cultivation and processing.

Conclusion

Makhana farming is a profitable activity for small and marginal farmers, who have stagnant water bodies, low-lying land, ponds and waterlogged land. The crop grows well in local conditions, requires less fertiliser and chemicals, and can be integrated with fish farming or grown in rice fields. Makhana has many more medicinal values due to its high nutritional value and health benefits. The demand for Makhana is increasing day by day in the international market, particularly in Western countries. It is suitable for small and marginal farmers of the Mallah community and a source of employment generation for rural families from Pond to Packet. Makhana helps farmers grow better crops with less effort and loss. Cultivation practices such as proper selection of varieties, suitable pond management, balanced nutrient application, timely weed control, and improved harvesting and popping techniques help reduce losses and increase efficiency. Adoption of modern tools and skill-based processing methods not only saves labour and time but also ensures better expansion, taste, and market value of makhana.

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