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FUTURE-READY AGRICULTURE

*Technology, Innovation
and Resilient Farming*

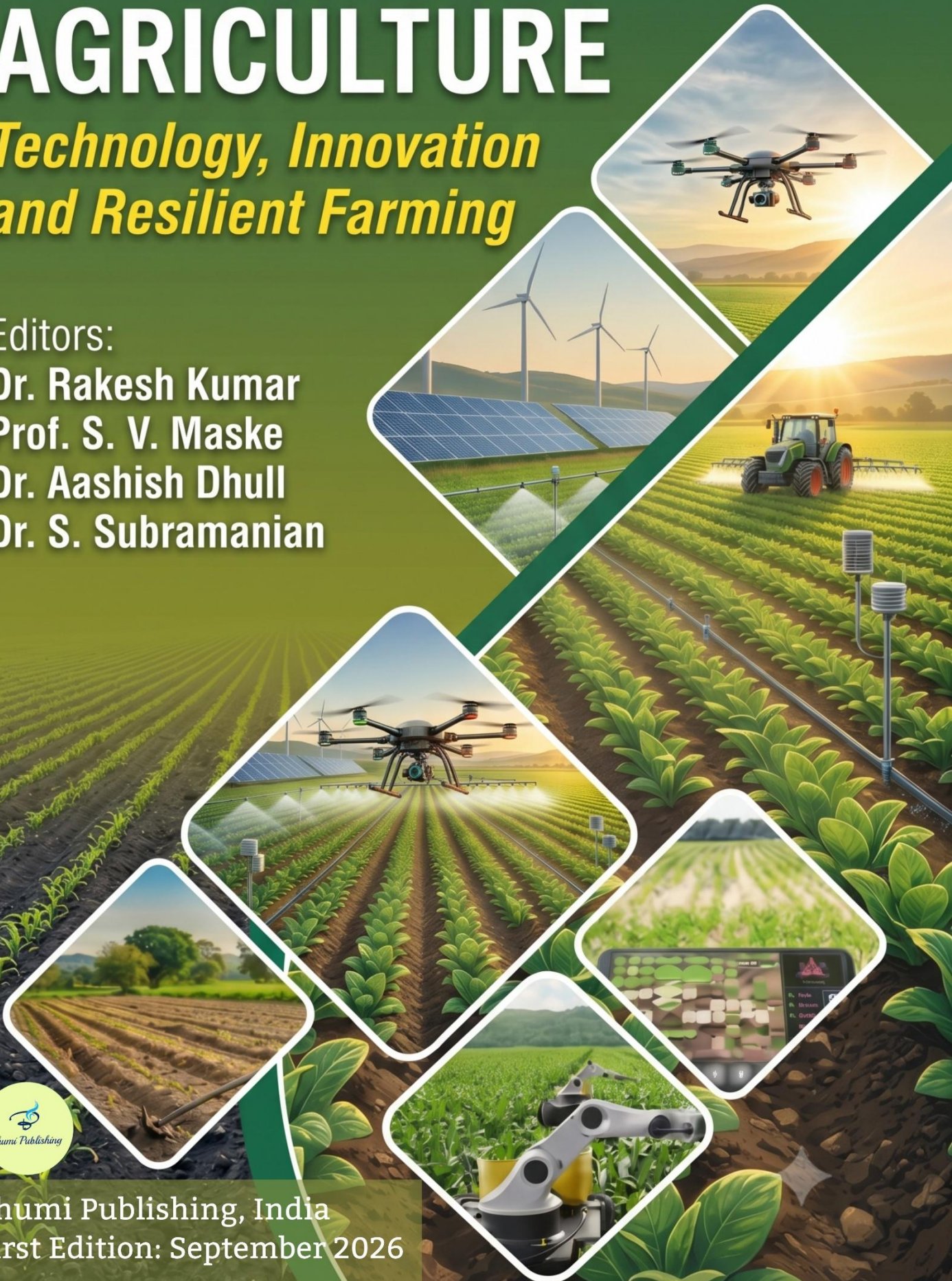
Editors:

Dr. Rakesh Kumar

Prof. S. V. Maske

Dr. Aashish Dhull

Dr. S. Subramanian



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Future-Ready Agriculture: Technology, Innovation and Resilient Farming

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Editors

Dr. Rakesh Kumar

Department of Mechanical Engineering,
Guru Jambheshwar University of Science &
Technology (GJUS&T), Hisar, Haryana

Prof. (Dr.) S. V. Maske

Department of Zoology,
Shri Vijaysinha Yadav College,
Peth Vadgaon, Dist. Kolhapur, M.S.

Dr. Aashish Dhull

Department of Veterinary Gynaecology and
Obstetrics, MR college of Veterinary Science
and Research Center, Jhajjar, Haryana

Dr. S. Subramanian

Department of Nautical Science,
AMET University,
Chennai, Tamil Nadu



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E-mail: bhumipublishing@gmail.com



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PREFACE

Agriculture is entering an era of profound transformation shaped by technological advancement, environmental challenges, changing consumer demands, and the need for sustainable food production. The book *Future-Ready Agriculture: Technology, Innovation and Resilient Farming* brings together contemporary perspectives on how scientific knowledge, digital technologies, and innovative practices can strengthen agricultural systems and prepare them for emerging challenges.

Modern agriculture increasingly integrates precision farming, artificial intelligence, machine learning, remote sensing, geographic information systems, drones, robotics, Internet of Things devices, and data-driven decision-making. These technologies enable farmers and agricultural professionals to monitor crops, optimize the use of water and fertilizers, identify pests and diseases, improve productivity, and reduce production costs. At the same time, biotechnology, improved crop varieties, protected cultivation, smart irrigation, and sustainable soil-management practices are creating new opportunities for efficient and resource-conscious farming.

Climate change, water scarcity, soil degradation, biodiversity loss, market uncertainty, and fluctuating input costs emphasize the importance of resilience. Future-ready agriculture therefore requires approaches that combine productivity with ecological sustainability, economic viability, and social inclusiveness. Climate-smart farming, regenerative agriculture, integrated pest management, conservation agriculture, agroforestry, and circular approaches to agricultural production can contribute to more adaptable and sustainable food systems.

This book provides a multidisciplinary platform for researchers, academicians, agricultural professionals, students, policymakers, and practitioners to explore emerging developments across agriculture and allied fields.

The volume also emphasizes the importance of knowledge, innovation, collaboration, and capacity building in shaping the agriculture of tomorrow. By connecting scientific research with field-level applications, it seeks to encourage informed decision-making and responsible technological adoption. It is hoped that this book will contribute to ongoing discussions on building productive, sustainable, inclusive, and resilient agricultural systems capable of meeting the food and livelihood needs of future generations.

- Editors

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SMART FARMING AND NEXT-GENERATION AGRICULTURE: REIMAGINING AGRICULTURAL EXTENSION FOR THE DIGITAL ERA

I. Venkata Reddy*, M. Ravi Kishore, P. N. Siva Prasad,

R. Prabhavathi, N. Rajasekhar, K. Lakshmi Kala and T. Jeswanth Reddy

Dr. K. I. Rao Krishi Vigyan Kendra, Garikapadu, NTR District, Andhra Pradesh, India.

*Corresponding author E-mail: ivrextedu18@gmail.com

Abstract

Agricultural extension is undergoing its most consequential transformation since the diffusion of the Training and Visit system in the 1970s. The convergence of precision agriculture, the Internet of Things, artificial intelligence, mobile connectivity, and data-driven advisory platforms is redrawing the boundaries of what "extension" means and who delivers it. This chapter examines how smart farming technologies are reshaping the design, delivery, and evaluation of extension services, with particular attention to the institutional role of frontline systems such as Krishi Vigyan Kendras (KVKs) in India. It surveys the core technological pillars of next-generation agriculture, analyses emerging delivery models that blend digital and human touchpoints, draws on field-level illustrations from India and comparable developing-country contexts, and identifies the capacity-building, infrastructural, and policy conditions required for equitable adoption. The chapter argues that the future of extension lies not in replacing extension functionaries with technology, but in equipping them as digitally fluent intermediaries who can translate complex data streams into locally meaningful, actionable advice for smallholder farmers.

Keywords: Smart Farming, Agricultural Extension, Digital Advisory, Precision Agriculture, Krishi Vigyan Kendra, ICT for Development, Farmer Field School, Extension 4.0.

Introduction

For much of the twentieth century, agricultural extension operated on a broadly linear model: research generated at universities and institutes was packaged by extension functionaries and transmitted to farmers through demonstrations, farm visits, and printed literature. This model served its era well, underpinning the diffusion of Green Revolution technologies across large parts of Asia. But it was built for a world of relatively homogeneous recommendations, slow-moving agronomic knowledge, and limited two-way feedback between the field and the laboratory. The world that today's extension systems operate in looks very different.

Climate variability has made generic, calendar-based advisories less reliable; input costs and market volatility have made timing and precision more consequential for farm profitability; and the rapid, near-universal penetration of mobile telephony in rural areas has created a channel for

advisory delivery that did not exist even fifteen years ago (Aker, 2011). At the same time, a new generation of technologies — sensors, satellites, drones, machine learning models, and blockchain-based traceability systems — has matured to the point where their cost has fallen within reach of public extension systems and even, in aggregated or subsidized forms, individual smallholders (Wolfert *et al.*, 2017).

This chapter treats "smart farming" not as a single technology but as a bundle of complementary capabilities: the ability to sense field and crop conditions with greater granularity, to process that information into decision-relevant advice, and to deliver that advice through channels farmers actually use. The chapter's central concern is extension — the institutional and human machinery that stands between what science and sensors can tell us and what a farmer standing in a field with a particular soil, a particular crop stage, and a particular cash-flow constraint actually needs to know today. It asks: what does smart farming demand of extension systems, and what must extension systems become to make smart farming useful rather than merely impressive?

The Changing Landscape of Agricultural Extension

Three shifts define the contemporary extension landscape. The first is a shift from generalized to personalized advisory. Traditional extension messaging — sown at this depth, apply this fertilizer dose, spray on this date — was necessarily pitched to an average farmer in an average field. Smart farming technologies make it possible, at least in principle, to tailor recommendations to an individual plot's soil test values, sowing date, variety, and real-time weather exposure. The second is a shift from push to pull, and from one-way to two-way communication. Where extension once flowed from expert to farmer through scheduled visits and print bulletins, mobile applications, interactive voice response (IVR) systems, and messaging-app-based farmer groups allow farmers to query, upload photographs of pest damage, and receive a response within hours rather than weeks. Extension is increasingly a dialogue mediated by data rather than a broadcast (Fabregas, Kremer and Schilbach, 2019).

The third is a shift in who delivers extension. Public extension systems — Krishi Vigyan Kendras, State Departments of Agriculture, and university extension wings — remain central, but they now operate alongside private agri-tech startups, farmer producer organizations (FPOs), input companies bundling advisory with sales, and platform companies offering AI-based diagnostic apps. Birner *et al.* (2009) describe this as a shift toward pluralistic advisory systems, which create both opportunity (more channels reaching more farmers) and risk (fragmented, sometimes contradictory advice, and commercial bias in privately delivered recommendations).

Three Structural Shifts in Extension

- From generalized, average-farmer advisories to plot- and farmer-specific recommendations
- From one-way broadcast to two-way, data-mediated dialogue between farmer and advisor

- From a public-extension monopoly to a pluralistic ecosystem of public, private, and cooperative advisory providers

Pillars of Smart Farming Technology

Smart farming rests on a set of interlocking technological capabilities. Extension functionaries need not become engineers or data scientists, but a working understanding of what each pillar does — and does not do — is essential to using these tools credibly with farmers.

1. Precision Agriculture and Remote Sensing

Precision agriculture uses spatial data — from satellite imagery, aerial photography, or ground-based sensors — to manage variability within a field rather than treating a field as a single uniform unit. Vegetation indices such as the Normalized Difference Vegetation Index (NDVI), derived from freely available satellite platforms, allow extension workers to identify patches of crop stress, uneven germination, or nutrient deficiency well before these are visible during a routine field visit. Soil mapping at sub-field resolution supports variable-rate application of fertilizer, reducing both cost and environmental runoff.

For extension purposes, the value of remote sensing lies less in the raw imagery than in its translation into a simple, actionable flag: this plot needs a visit, this zone needs a top-dressing of nitrogen, this field shows early signs of moisture stress. Several state agriculture departments and KVKs in India now receive such advisory triggers through partnerships with national remote-sensing agencies and agri-tech intermediaries, which extension staff then verify on the ground before communicating to farmers.

2. IoT and Sensor-Based Farm Monitoring

Internet of Things (IoT) devices — soil moisture probes, weather stations, and pest traps fitted with counting sensors — generate continuous, field-level data streams. Automated weather stations networked across a district can substantially improve the granularity of rainfall and temperature advisories compared to reliance on a single district-level reading. Soil moisture sensors linked to irrigation scheduling tools help reduce over-irrigation, a significant driver of both water waste and secondary problems such as waterlogging and salinity in canal-irrigated tracts.

The extension challenge with IoT is less technical than institutional: sensors generate data continuously, but few smallholders have the time, connectivity, or dashboard literacy to interpret a stream of numbers. This is precisely the translation role extension functionaries are positioned to play — converting a moisture-sensor reading into a one-line advisory such as "irrigate tomorrow morning" rather than expecting farmers to read raw sensor output themselves.

3. Artificial Intelligence and Decision Support Systems

Machine learning models now underpin a growing category of diagnostic and advisory tools: image-based pest and disease identification apps that let a farmer photograph a leaf and receive a

probable diagnosis; yield prediction models that combine weather, soil, and satellite data; and crop advisory chatbots that respond to farmer queries in natural language, including regional languages. These tools substantially lower the cost of a first-line diagnosis, which is valuable in areas where the ratio of extension functionaries to farm households remains far below recommended norms.

AI-based tools work best as a triage layer, not a replacement for expert judgement. Image-recognition models can misclassify look-alike symptoms — nutrient deficiency mimicking early blight, for instance — and can perform poorly on crop varieties or disease presentations under-represented in their training data. Extension systems adopting such tools should treat AI output as a prompt for verification rather than a final recommendation, and should maintain a feedback loop so that flagged misclassifications are reported back to the tool's developers.

4. Mobile and ICT-Based Advisory Platforms

Mobile telephony remains the single most consequential enabling technology for extension reach in the developing world, simply because penetration is now near-universal even in remote rural areas, while data and dashboard literacy are not (Aker, 2011). SMS-based advisories, IVR call-back services, and messaging-app-based farmer groups allow extension systems to reach farmer numbers that field visits alone could never cover. India's Kisan Call Centres, the mKisan SMS Portal, and a growing number of state-specific mobile applications exemplify this channel, as do farmer-facing apps developed by agricultural universities and private agri-tech firms.

Voice-based and vernacular-language interfaces deserve particular emphasis. A meaningful share of the smallholder farming population is more comfortable with spoken than written communication in the local language, and literacy constraints limit the reach of text-only advisory. IVR systems that deliver a short recorded advisory in the local dialect, updated on a rolling basis as crop stage and weather conditions change, have shown higher engagement among older and less-literate farmers than app-based, text-heavy alternatives.

5. Drones and Robotics in Field Operations

Unmanned aerial vehicles (drones) are increasingly used for two extension-relevant purposes: aerial crop surveillance at a resolution finer than satellite imagery but faster than a manual field walk, and precision spraying of pesticides, fertilizers, and plant growth regulators. Drone-based spraying reduces both the volume of chemical applied and human exposure to agrochemicals, an occupational health benefit that is under-discussed relative to its efficiency benefits.

Robotics adoption in smallholder contexts remains limited chiefly by cost and the fragmented, small average landholding size typical of much of South Asia, which makes capital-intensive robotic weeding or harvesting equipment difficult to justify for an individual farm household. Custom hiring centres — where KVKs, FPOs, or private operators own equipment and rent it out

per-acre or per-hour — are emerging as the institutional bridge that allows smallholders to access these technologies without individual ownership.

6. Blockchain and Supply Chain Traceability

Blockchain-based traceability systems record a tamper-resistant history of a produce batch from farm to retail, supporting quality certification, geographic-indication claims, and premium market access. While still at a relatively early and pilot stage of adoption among smallholders, such systems have extension relevance chiefly through the record-keeping discipline they require — accurate input application logs, harvest dates, and post-harvest handling records — which extension programmes are well placed to help farmers and FPOs establish and maintain.

Reimagining Extension Delivery

Technology pillars alone do not constitute extension; delivery models determine whether a technology's potential reaches a farmer's field. This section considers how established extension institutions and emerging channels are adapting.

1. Krishi Vigyan Kendras as Innovation Nodes

Krishi Vigyan Kendras occupy a distinctive position in India's extension architecture: district-level, multi-disciplinary institutions with a mandate spanning technology assessment, refinement, demonstration, training, and advisory services, with direct lines to both the national agricultural research system (ICAR, 2021) and state agricultural universities. This structure positions KVKs well to act as local validation nodes for smart farming technologies — testing a satellite-based advisory tool's recommendations against ground conditions in local agro-climatic contexts before those recommendations are scaled to farmers, and adapting nationally or internationally developed digital tools to local crop varieties, cropping calendars, and dialects.

In practice, this often takes the form of a KVK subject matter specialist reviewing an automated advisory generated for the district, checking it against field visits and farmer feedback, and only then relaying a confirmed, locally calibrated version to farmer groups or through village-level demonstrations. This human-in-the-loop model preserves the credibility that comes from a known, locally accountable extension worker while still benefiting from the reach and granularity that digital tools provide.

2. Farmer Field Schools 2.0

The Farmer Field School (FFS) model — season-long, group-based, experiential learning built around a farmer-managed comparison plot — has proven durable because it builds farmer capacity to observe and decide rather than simply to follow instructions. Digital tools are increasingly layered onto this model rather than replacing it: FFS groups use smartphone cameras to document pest counts and share images within the group's messaging thread for peer and expert comment, and satellite-derived NDVI maps are projected during group sessions to help farmers visually connect within-field variability to their own observations.

3. Digital Kiosks, Common Service Centres, and Village-Level Entrepreneurs

Where individual smartphone ownership or data affordability remains a constraint, shared-access models fill the gap. Common Service Centres, village-level digital kiosks, and trained village-level entrepreneurs provide a local point of access where a farmer can bring a query, a soil sample, or a pest sample, and receive digitally sourced advisory translated into a locally understandable recommendation. These intermediary roles also address a persistent digital-divide concern: they extend the reach of smart farming tools to farmers who would otherwise be excluded by a purely app-based delivery model.

4. Vernacular Content and Voice-Based Advisory

Content localisation is not a cosmetic add-on but a determinant of adoption. Advisory content — whether SMS text, IVR recordings, or short videos — needs to be produced in the farmer's spoken dialect, use locally recognisable crop-stage terminology, and reference locally known pest and disease names rather than only their scientific nomenclature. Extension systems that have invested in vernacular content libraries report materially higher farmer engagement than those relying on translated but culturally generic content.

5. Case Illustrations from India and Beyond

A number of documented initiatives illustrate how the elements above combine in practice.

Table 1: Illustrative smart-farming-enabled extension initiatives and the extension function each primarily demonstrates

Initiative / Programme	Core Technology	Extension Role Illustrated
Kisan Call Centres / mKisan Portal (India)	IVR, bulk SMS advisory	Mass, low-literacy-friendly reach with query-response capability
e-NAM (National Agriculture Market)	Digital trading platform	Market-linked advisory alongside price discovery
Digital Green's video-based extension model	Locally produced farmer-to-farmer video	Peer-credible, vernacular knowledge transfer at community screenings
Satellite-based pest and weather advisories via KVK networks	Remote sensing, automated weather stations	Human-verified, locally calibrated digital-to-analog translation
Custom hiring centres for drones and farm machinery	Drones, precision equipment	Shared-access model overcoming smallholder capital constraints

Beyond India, comparable models are visible across South and Southeast Asia and parts of sub-Saharan Africa, where mobile-money-linked advisory bundles, satellite-based drought index insurance triggers, and farmer-to-farmer video extension have been documented as improving both the reach and the specificity of advisory services relative to conventional visit-based

extension alone (FAO, 2023). A recurring theme across these cases is that technology adoption succeeds where it is embedded within, rather than substituted for, a trusted local institutional relationship.

6. Capacity Building of Extension Functionaries

The single most consistently cited bottleneck in smart-farming-enabled extension is not the availability of technology but the digital and analytical capacity of the extension workforce itself. Subject Matter Specialists and frontline extension workers were, for the most part, trained in an era when the core professional skill set was agronomic and communicative rather than data-analytical. Closing this gap requires deliberate, structured capacity building along at least four dimensions.

- Digital literacy: comfort navigating dashboards, mobile applications, and basic data visualisation, sufficient to interpret and explain digital tools.
- Data interpretation: the judgement to translate a satellite-derived stress index, a sensor reading, or an AI-flagged diagnosis into field-verified, locally appropriate advice.
- Content creation: the ability to produce short, vernacular, farmer-facing advisory content — text, audio, or video — rather than relying solely on centrally produced material.
- Institutional brokering: the relational skill of connecting farmers, FPOs, agri-tech providers, input companies, and research institutions.

Structured in-service training — through ICAR's KVK training calendars, State Agricultural Management and Extension Training Institutes (SAMETIs), and short digital-skills modules embedded within existing refresher courses — is the most immediately actionable lever available to extension administrations, since it works within existing institutional structures rather than requiring new cadre creation (Kumar *et al.*, 2020).

7. Challenges and Barriers to Adoption

7.1 Infrastructural and Connectivity Constraints

Reliable mobile network coverage, affordable data, and consistent electricity supply remain uneven across rural India and much of the developing world, particularly in hilly, forested, and other remote agro-climatic zones. Smart farming tools that assume continuous connectivity or smartphone ownership can inadvertently exclude precisely the farmers who stand to benefit most from improved advisory access.

7.2 The Digital Divide Within Farming Communities

Even where connectivity exists, adoption is uneven along lines of age, gender, landholding size, and literacy. Women farmers, who perform a substantial share of agricultural labour in many regions, are frequently under-represented as direct recipients of digital advisory because mobile phone ownership and access within a household often skew toward male members. Extension

programmes that do not deliberately design for this gap risk widening rather than narrowing existing inequities in access to agricultural information.

7.3 Data Quality, Trust, and Liability

Advisory generated from remote or automated sources is only as reliable as its ground-truthing. A satellite-based moisture-stress flag that does not match a farmer's own field observation erodes trust not only in that specific tool but in digital advisory more broadly. Questions of liability — who is responsible when an automated recommendation leads to crop loss — remain largely unresolved in most extension systems and warrant clearer institutional and, where relevant, regulatory guidance.

7.4 Fragmentation and Commercial Bias

The pluralism of advisory sources discussed in Section 3.2 carries a risk of contradictory messaging reaching the same farmer from public extension, input-company representatives, and app-based platforms, some of which may have a commercial interest in recommending particular inputs. Coordination mechanisms — district-level advisory convergence committees, for instance — can help align messaging without suppressing the genuine value that private-sector innovation contributes.

7.5 Cost and Sustainability of Technology Deployment

Sensor networks, drone fleets, and satellite subscriptions carry recurring costs that are often underestimated relative to the one-time capital cost emphasised in project proposals. Extension systems adopting these tools need realistic operational-cost planning, including maintenance, calibration, and eventual technology replacement, to avoid a pattern of well-funded pilots that lapse once initial project funding ends.

8. Policy Imperatives and Institutional Convergence

Realising the potential of smart farming for extension requires action on several fronts simultaneously, since technology, institutional capacity, and policy are mutually reinforcing rather than independently sufficient (Ministry of Agriculture and Farmers Welfare, 2022).

Policy and Institutional Priorities

- Expand rural digital and electricity infrastructure with explicit attention to underserved and remote agro-climatic zones
- Institutionalise in-service digital-skills training for extension functionaries within existing training calendars (KVK, SAMETI, state extension departments)
- Establish district- or block-level convergence platforms to coordinate messaging across public, private, and cooperative advisory providers
- Invest in vernacular, voice-first content libraries as a core extension deliverable rather than a supplementary output

- Design deliberately for gender-equitable and smallholder-inclusive access, including shared-access models where individual device ownership is limited
- Build data governance and liability frameworks that clarify responsibility for automated advisory outcomes
- Fund operational and maintenance costs of digital infrastructure over multi-year horizons, not only initial procurement

Institutional convergence — between ICAR institutes, state agricultural universities, State Departments of Agriculture, FPOs, and private agri-tech actors — is as important as any single technological investment. No single institution possesses the full stack of research depth, last-mile reach, digital platform capability, and market linkage that next-generation extension requires; the practical task ahead is coordinating these distinct strengths around a shared, farmer-centred advisory agenda rather than duplicating effort across parallel systems.

9. The Road Ahead: Extension 4.0

Looking forward, the trajectory of agricultural extension is likely to be defined by what might be termed Extension 4.0: an extension system in which digital sensing, AI-assisted interpretation, and human field verification operate as a single integrated advisory pipeline, rather than as separate, loosely connected initiatives. In this model, the extension functionary's core value shifts from being a primary source of technical knowledge — a role increasingly shared with digital tools — to being a trusted, locally accountable interpreter, verifier, and relationship-holder, whose judgement determines which of the many available digital signals actually merit a farmer's attention on a given day.

This shift does not diminish the importance of the extension workforce; if anything, it raises the bar for what that workforce must be able to do, replacing rote message delivery with a more demanding synthesis role. Institutions that invest early in preparing their extension functionaries for this role are likely to be best positioned to convert the technological promise of smart farming into measurable gains in farm productivity, resource-use efficiency, and farmer income.

Conclusion

Smart farming technologies — precision agriculture, IoT sensing, artificial intelligence, mobile advisory platforms, drones, and blockchain-based traceability — offer agricultural extension systems capabilities that were unavailable even a decade ago: finer-grained diagnosis, faster feedback loops, and reach into farmer populations that visit-based extension alone could never adequately cover. Yet none of these capabilities substitutes for the institutional trust, local calibration, and human judgement that extension systems such as Krishi Vigyan Kendras have built over decades. The chapter's central argument is that the future of agricultural extension lies in a deliberately hybrid model: digital tools generating and surfacing information at a scale and granularity impossible for field visits alone, and extension functionaries — supported by

structured capacity building, coordinated institutional convergence, and inclusive delivery design — verifying, localising, and delivering that information in a form smallholder farmers can trust and act on. Realising this model at scale is less a technology challenge than an institutional and human-capacity one, and it is on that front that policy attention and investment are now most needed.

References

1. Adesina, A. A., & Zinnah, M. M. (1993). Technology characteristics, farmers' perceptions and adoption decisions. *Agricultural Economics*, 9(4), 297–311.
2. Aker, J. C. (2011). Dial "A" for agriculture: A review of information and communication technologies for agricultural extension in developing countries. *Agricultural Economics*, 42(6), 631–647.
3. Birner, R., Davis, K., Pender, J., Nkonya, E., Anandajayasekeram, P., Ekboir, J., Mbabu, A., Spielman, D. J., Horna, D., Benin, S., & Cofini, F. (2009). From best practice to best fit: A framework for designing and analyzing pluralistic agricultural advisory services worldwide. *Journal of Agricultural Education and Extension*, 15(4), 341–355.
4. Fabregas, R., Kremer, M., & Schilbach, F. (2019). Realizing the potential of digital development: The case of agricultural advice. *Science*, 366(6471), 1–8.
5. Food and Agriculture Organization of the United Nations. (2023). *The state of food and agriculture 2023: Digital agriculture and smallholder farmers* (Vol. 1, pp. 1–180). FAO.
6. Glendenning, C. J., Babu, S., & Asenso-Okyere, K. (2010). *Review of agricultural extension in India: Are farmers' information needs being met?* (IFPRI Discussion Paper 01048, Vol. 1, pp. 1–48). International Food Policy Research Institute.
7. Indian Council of Agricultural Research. (2021). *Krishi Vigyan Kendra: Guidelines for implementation* (Vol. 1, pp. 1–60). ICAR-Agricultural Technology Application Research Institute.
8. Kumar, A., Takeshima, H., Thapa, G., Adhikari, N., Saroj, S., Karkee, M., & Joshi, P. K. (2020). Adoption and diffusion of improved technologies and production practices in agriculture. *Land Use Policy*, 95, 104621.
9. Ministry of Agriculture and Farmers Welfare, Government of India. (2022). *Digital agriculture: Framework and mission document* (Vol. 1, pp. 1–40). Department of Agriculture and Farmers Welfare.
10. Wolfert, S., Ge, L., Verdouw, C., & Bogaardt, M. J. (2017). Big data in smart farming—A review. *Agricultural Systems*, 153, 69–80.
11. Digital Green. (n.d.). *Farmer-to-farmer video-based extension model*. <https://digitalgreen.org>

INTEGRATING TRADITIONAL WISDOM WITH SMART AGRICULTURE: DIGITAL EXTENSION FOR NATURAL FARMING ADOPTION

I. Venkata Reddy*, M. Ravi Kishore, P. N. Siva Prasad,

R. Prabhavathi, N. Rajasekhar, K. Lakshmi Kala and T. Jeswanth Reddy

Dr. K. I. Rao Krishi Vigyan Kendra, Garikapadu, NTR District, Andhra Pradesh, India.

*Corresponding author E-mail: ivrextedu18@gmail.com

Abstract

India's agricultural extension system has historically struggled to reach the country's more than 140 million operational holdings with timely, location-specific advice, even as decades of chemical-intensive cultivation have degraded soil health, raised input costs, and increased farmer indebtedness. At the same time, traditional and community-evolved practices of low-cost, input-light cultivation — collectively described today as natural farming — have re-emerged as a scientifically credible and economically viable alternative, most visibly through the Andhra Pradesh Community Managed Natural Farming (APCNF) programme. This chapter examines how digital extension tools can be deployed not to replace this traditional wisdom but to scale it: standardising and disseminating protocols for bio-inputs such as Jeevamrutham and Beejamrutham, popularising natural seed pelletization using locally available materials, and using community radio, participatory video and social media to drive sustained behaviour change among farmers. Drawing on evidence from the APCNF experience, Digital Green's community video model, and mobile-based advisory platforms such as mKisan and the Kisan Call Centre, the chapter develops an integrated framework in which digital tools function as force-multipliers for peer-to-peer, trust-based extension rather than as substitutes for it. The chapter concludes that "smart farming" need not be equated only with sensors, drones and artificial intelligence; it can equally mean the intelligent, technology-assisted scaling of ecologically sound, low-cost, traditional agricultural wisdom, and outlines policy directions for institutionalising this approach within India's next generation of agricultural extension.

Keywords: Natural Farming, Digital Extension, Jeevamrutham, Bio-Fertilizers, Seed Pelletization, Community Radio, Behaviour Change, Sustainable Agriculture.

1. Introduction

Indian agriculture stands at a crossroads. The productivity gains of the Green Revolution were built on a package of high-yielding varieties, synthetic fertilizers, irrigation expansion and chemical pesticides, and these gains are now widely acknowledged to have come at a cost to soil organic matter, groundwater tables, input economics and farmer health. Rising cultivation costs alongside stagnating or volatile output prices have squeezed farm incomes, and this cost-price

squeeze is repeatedly cited as a contributing factor in rural distress in rain-fed and dryland regions. Against this backdrop, natural farming has gained renewed policy and academic attention as a pathway that can lower input costs, rebuild soil biology, and improve the resilience of smallholder systems to climate variability.

Natural farming is not a new invention. Its core techniques — fermenting cow dung and urine into microbial inoculants, treating seed with local materials before sowing, keeping the soil continuously covered, and timing irrigation to soil moisture rather than a fixed calendar — draw on generations of farmer-evolved knowledge that predates the input-intensive model. What natural farming programmes such as Andhra Pradesh's have done is codify this traditional wisdom into replicable protocols, and it is precisely at the point of replication and scale that digital extension tools become relevant.

This chapter argues that the future of "smart farming" in India should not be understood narrowly as a story of sensors, drones and artificial intelligence layered onto an unchanged chemical-input model. A more inclusive and more immediately actionable understanding of smart agriculture is the intelligent, technology-assisted scaling of low-cost, ecologically sound, traditional practices — using mobile phones, community video, radio and social media not to replace the farmer-to-farmer trust networks that have always driven adoption, but to extend their reach. The chapter is organised as follows: Section 2 revisits the case for traditional agricultural wisdom; Section 3 describes the core technical practices of natural farming; Section 4 reviews the evolution of digital extension in India; Section 5 proposes an integrated framework across three domains — bio-fertilizer promotion, seed pelletization protocol dissemination, and community radio/social media-based behaviour change; Section 6 presents field evidence; Section 7 develops a behaviour-change communication model; Section 8 discusses barriers; and Section 9 offers policy recommendations.

2. Traditional Wisdom in Indian Agriculture: A Foundation for Sustainability

Long before the vocabulary of "soil microbiome" entered agricultural science, Indian cultivators practised forms of nutrient recycling built around livestock integration: dung and urine were composted or fermented and returned to the field, crop residues were retained or grazed rather than burnt, and mixed and rotational cropping was used to manage pest pressure and spread risk across seasons. These practices were locally calibrated — the specific plants used in a fermented preparation, the timing of sowing, or the choice of intercrops varied by agro-climatic zone — which is precisely what made them resilient but also difficult to standardise and transmit outside the community in which they evolved.

The erosion of this knowledge base over the second half of the twentieth century was not simply a matter of farmers abandoning tradition; it reflected a policy and market architecture that subsidised chemical inputs, built extension systems around a linear transfer-of-technology

model, and rewarded short-term yield response over long-term soil health. Reviving traditional practice at scale therefore requires more than nostalgia: it requires (a) documenting and standardising practices into protocols that a first-generation adopter can follow without decades of embodied experience, and (b) building extension channels capable of reaching that adopter repeatedly, in their own language, at the moments in the cropping calendar when the information is actionable. This is the gap that digital tools are increasingly being used to fill, working alongside rather than instead of the community institutions — farmer groups, self-help groups and community resource persons — that have historically carried this knowledge.

3. Natural Farming Practices and Their Scientific Rationale

Contemporary natural farming programmes in India, most prominently the model popularised by Subhash Palekar and scaled by the Andhra Pradesh government as Zero Budget Natural Farming (ZBNF) and subsequently rebranded Andhra Pradesh Community Managed Natural Farming (APCNF), are generally organised around four interlinked practices.

3.1 Beejamrutham (Seed Treatment) and Natural Seed Pelletization

Beejamrutham is a seed and root treatment prepared from cow dung, cow urine, lime and a handful of soil, in which seed is coated before sowing to protect young roots from soil-borne fungal pathogens during the vulnerable early monsoon period. Natural seed pelletization extends this principle: seed is coated in successive layers of locally sourced material — fine farm soil or compost, a binder, and a microbial inoculant such as Jeevamrutham or Ghana Jeevamrutham (a concentrated, solid form of the same fermented preparation) — to improve seed-soil contact, protect against early pest and disease pressure, and in some protocols to carry beneficial microbial inoculum directly into the root zone. Because pelletization is a physical, sequential process, it is unusually well suited to demonstration through short video: each layer, drying time and consistency check can be shown rather than described in text, which is a recurring justification in the extension literature for using participatory video for this class of practice.

3.2 Jeevamrutham and Ghana Jeevamrutham (Bio-fertilizer/Microbial Inoculant)

Jeevamrutham is a fermented liquid preparation of fresh cow dung, aged cow urine, jaggery, pulse flour and a handful of undisturbed field-bund soil (used as a natural microbial starter culture), left to ferment for several days and applied to the soil, typically through irrigation water. The stated agronomic function of Jeevamrutham is to rapidly multiply beneficial soil microorganisms — including nitrogen-fixing and phosphorus-solubilising bacteria and decomposer fungi — which in turn accelerate the breakdown of organic matter already present in the soil and improve nutrient availability to the crop, rather than supplying nutrients directly as a chemical fertilizer does. Ghana Jeevamrutham, the semi-solid, dried variant, was developed for ease of storage, transport and broadcast application, and features prominently in seed pelletization protocols. Because both preparations depend on fermentation conditions

(temperature, timing, ingredient ratios) that are easy to get wrong, standard operating protocols with clear visual and time cues are considered important for consistent quality when the practice is scaled beyond the original innovating community.

3.3 Acchadana (Mulching) and Whapasa (Soil Aeration/Moisture Management)

Acchadana refers to the practice of keeping the soil continuously covered — through crop residue, live mulch or standing biomass — to moderate soil temperature, suppress weeds, conserve moisture and feed soil organisms as the mulch decomposes. Whapasa describes a soil-moisture philosophy in which irrigation is calibrated to maintain a balance of air and water in the soil pore space rather than saturating the root zone, on the reasoning that continuously waterlogged soil suppresses the aerobic microbial activity that the other three practices are designed to build up. Together, the four practices are presented in programme literature not as a checklist of discrete inputs to be purchased, but as a mutually reinforcing system for rebuilding soil biological activity.

4. Digital Extension: Concept and Evolution in Indian Agriculture

Agricultural extension in India has moved through several distinct phases: the classical Training-and-Visit system of periodic in-person contact between government extension officers and a designated group of contact farmers; broadcast media such as the long-running television programme *Krishi Darshan* and All India Radio's farm broadcasts; the establishment of *Krishi Vigyan Kendras* (farm science centres) as local hubs of demonstration and advice; and, since the 2000s, a rapidly expanding set of information and communication technology (ICT) tools. These ICT-based tools include the Kisan Call Centre, a toll-free telephone advisory staffed by subject-matter experts in local languages; the mKisan portal and associated SMS/mobile advisory services, which push crop-, weather- and market-specific alerts directly to registered farmers' phones; and participatory video platforms such as Digital Green, which record local farmers demonstrating a practice and screen the resulting short videos in small peer-group settings, often paired with a human facilitator.

A recurring finding across evaluations of these platforms is that technology alone rarely drives adoption of a new practice; what drives adoption is technology embedded in a trusted social process — a known facilitator, a peer farmer as presenter, a group viewing setting that allows questions and social reinforcement. This finding is central to the argument of this chapter: digital extension is best understood not as a replacement for face-to-face, community-based extension, but as a way of multiplying its reach, standardising its content, and making it repeatable at low marginal cost once produced.

At the same time, evaluations of ICT-based extension in India and elsewhere point to persistent constraints — uneven smartphone and internet access, low digital literacy among older and less-educated farmers, unreliable rural electricity and connectivity, and gender gaps in mobile phone

ownership and control within farm households — all of which shape how any digital extension strategy for natural farming needs to be designed, a point taken up further in Section 8.

5. A Framework for Integrating Traditional Wisdom with Digital Extension

Building on the practices described in Section 3 and the tools described in Section 4, this section proposes an integrated framework across three domains identified as priorities for natural farming extension: bio-fertilizer promotion, seed pelletization protocol dissemination, and community radio/social media-driven behaviour change.

5.1 Digitally-Enabled Promotion of Bio-Fertilizers

Preparations such as Jeevamrutham are sensitive to fermentation timing, temperature and ingredient ratios, and small errors are difficult to diagnose from written instructions alone. A digital extension approach treats the preparation process itself as content: short, locally-shot videos can show the correct consistency, colour and smell of the ferment at each stage; SMS or app-based reminders can be timed to the cropping calendar to prompt farmers to prepare a fresh batch before a critical application window; and a simple photo-based query feature — a farmer photographing their ferment and sending it to a facilitator or WhatsApp group for a quick visual check — substitutes for an in-person quality check that would otherwise require a scarce extension officer to travel to the farm. Aggregated, anonymised queries of this kind can also help identify where local training needs to be reinforced, turning routine advisory contact into a low-cost monitoring signal for programme managers.

5.2 Disseminating Protocols for Natural Seed Pelletization

Because pelletization is a sequential, hands-on process, it is a strong candidate for short-form video and step-card style content of the kind increasingly shared through farmer WhatsApp groups and YouTube channels operated by Krishi Vigyan Kendras, state agricultural universities and non-governmental extension partners. A standard protocol — cleaning and pre-treating seed, preparing the Ghana Jeevamrutham coating, applying successive thin layers with adequate drying time between coats, and correctly storing pelletized seed until sowing — can be broken into short, single-step video clips of the kind pioneered by Digital Green's model, so that a farmer can review just the step they are unsure about rather than sitting through a lengthy training session again. Making the same protocol available as a one-page pictorial card (for offline reference) and as a spoken-language audio note (for farmers with low literacy) further widens the audience that a single production effort can reach.

5.3 Community Radio and Social Media for Behaviour Change

Community radio retains a distinct advantage for natural farming extension in that it reaches farmers without a smartphone or reliable data connection, can be consumed while doing farm work, and — because community radio stations are locally licensed and often locally staffed — can broadcast in hyper-local dialects and reference locally relevant crops and seasons. Farmer

call-in segments, in which practitioners of natural farming answer questions from other listeners on air, replicate at low cost the peer-credibility that has been identified as central to adoption in face-to-face extension models. Social media platforms — short-video formats, WhatsApp farmer groups organised by block or crop, and Facebook groups run by Farmer Producer Organisations — extend this further among younger and more digitally connected farmers, and are increasingly used to circulate testimonial content in which early adopters describe input-cost savings and yield outcomes in their own words, a format that behaviour-change communication research consistently finds more persuasive than expert-delivered instructional content alone.

6. Evidence from the Field: Selected Case Studies

6.1 Andhra Pradesh Community Managed Natural Farming (APCNF)

Andhra Pradesh's natural farming programme, implemented through the state-promoted non-profit Rythu Sadhikara Samstha (RySS), began as a pilot in 2015-16 and set an initial ambition of reaching all of the state's roughly six million farmers by 2024. The programme is distinctive for building its extension model around Community Resource Persons — experienced farmer-practitioners trained to mentor other farmers within their own village and social network — rather than relying solely on government extension staff, effectively formalising the same peer-to-peer trust dynamic on which traditional knowledge transmission always depended. Independent field-trial research across multiple districts has reported that natural farming plots show no short-term yield penalty relative to conventional or organic comparison plots, alongside evidence of improved farmer-reported crop resilience to dry spells, while academic assessments of the programme's scale-up have highlighted the multi-layered community institutional structure — organised across zones, Gram Panchayats and farmer clusters — as central to how the programme has been able to grow beyond its original pilot villages.

6.2 Digital Green's Video-Mediated Extension Model

Digital Green, founded in India in 2008, produces short videos in which local farmers demonstrate agricultural practices in their own language and dialect, which are then screened by a trained community facilitator to small farmer groups using a low-cost pico-projector, with the facilitator pausing the video to answer questions and record attendance and stated intention to adopt. In a controlled multi-village trial, this model was found to increase adoption of the practices demonstrated several-fold compared with a classical government training-and-visit approach, at a substantially lower cost per farmer reached, and subsequent randomised evaluations conducted with India's National Rural Livelihood Mission self-help group network found that incorporating short instructional videos into existing group meetings improved women farmers' reported productivity and profits at low additional cost. The model's design choices — hyper-local presenters, small peer-group viewing rather than solitary viewing, and a

human facilitator rather than a video-only delivery — are directly transferable to natural farming content of the kind described in Section 5.

6.3 Mobile and Call-Centre Based Advisory: mKisan and the Kisan Call Centre

The mKisan platform and its associated SMS advisory service push crop-stage-specific, weather-linked and market-price alerts to registered farmers' mobile phones in their preferred language, while the Kisan Call Centre provides a toll-free number connecting farmers to agricultural experts for two-way, spoken-language query resolution. Reviews of India's broader digital agriculture push, including these platforms alongside Aadhaar-linked direct benefit transfer of subsidies, describe improved access to timely information on weather, pest management and market trends as a consistent benefit, while also flagging the same access and literacy constraints noted in Section 4. For natural farming specifically, these channels offer a low-cost mechanism for time-bound reminders — for example, prompting farmers to begin a fresh Jeevamrutham ferment a set number of days before a scheduled irrigation — that complement the richer but less frequent video and radio content described above.

7. A Behaviour-Change Communication Model for Natural Farming Adoption

The case evidence in Section 6 points toward a common structure that can be generalised into a four-stage behaviour-change communication model for natural farming adoption through digital extension.

- Awareness: Community radio spots, social media testimonials and mass SMS alerts introduce the practice and its rationale to the widest possible audience at low cost per contact.
- Demonstration: Short, locally-presented video content — following the Digital Green model — shows the practice being performed correctly by a recognisable peer, addressing the "how exactly do I do this" gap that text-only communication leaves open.
- Trial support: Facilitated peer group viewing, WhatsApp query groups and Kisan Call Centre access allow a farmer attempting the practice for the first time to get a quick answer or a visual quality check during the trial period, when the risk of a small preparation error discouraging further adoption is highest.
- Reinforcement and social proof: Community Resource Person mentoring, farmer testimonial content and repeat radio call-in segments sustain the practice into subsequent seasons and use visible peer adoption to influence still-undecided farmers in the same community.

This model deliberately does not place digital tools at every stage in the same role. Broadcast tools (radio, mass SMS, social media) are best suited to the awareness stage, where reach matters more than depth; person-mediated, video-supported tools are best suited to demonstration and trial support, where fidelity of technique matters most; and community institutional structures —

self-help groups, farmer clusters, Community Resource Persons — remain central to reinforcement, which is consistent with the extension literature's broader finding that technology functions best as an amplifier of, rather than a substitute for, trusted social networks.

8. Challenges and Barriers

- Digital divide: Uneven smartphone ownership, data affordability and rural connectivity limit the reach of app- and video-based tools, particularly among older, less-educated and women farmers, making community radio and facilitator-mediated group viewing important complements rather than optional extras.
- Quality control of user-generated content: As natural farming content spreads through informal social media and WhatsApp forwards, unverified or locally distorted versions of protocols can circulate alongside accurate ones, underscoring the need for a small number of verified, institutionally-endorsed reference videos that other content can be checked against.
- Language and dialect diversity: Written protocols and even standard-language video content can fail to reach farmers who are most comfortable in a local dialect, which is precisely the gap that locally staffed community radio and locally presented Digital Green-style video are designed to close, but which requires sustained local content production rather than one-off translation.
- Verification of preparation quality: Unlike a purchased fertilizer with a standard nutrient content, farm-prepared Jeevamrutham quality varies with local materials and technique, and digital tools can prompt and remind but cannot substitute for the periodic in-person or photo-based quality checks discussed in Section 5.1.
- Institutional coordination: Sustained integration of traditional practice and digital tools requires coordination across state agriculture departments, Krishi Vigyan Kendras, non-profit extension partners and community radio licensees, and can be undermined by short project cycles or a single agency's platform being discontinued after donor or programme funding ends.

9. Policy Recommendations and the Way Forward

- Institutionalise a small library of verified, multi-language reference videos for core practices (Jeevamrutham preparation, Beejamrutham treatment, seed pelletization, mulching) produced with state agricultural universities and Krishi Vigyan Kendras, so that informally circulating social media content has an authoritative version to be checked against.
- Expand Community Resource Person-style peer mentoring models, piloted at scale in Andhra Pradesh, to other states adopting natural farming, using digital tools to support

(scheduling, content access, query routing) rather than replace the mentor-farmer relationship.

- Integrate natural farming content into existing mobile advisory infrastructure (mKisan, Kisan Call Centre) as a dedicated content stream with crop-calendar-linked reminders, rather than requiring a separate platform that adds to farmers' digital-tool burden.
- Sustain and expand community radio partnerships specifically for natural farming, given their reach among farmers without smartphone or data access, and use farmer call-in formats to preserve the peer-credibility shown to matter for adoption.
- Build simple photo- or short-video-based quality-check features into farmer-facing apps or WhatsApp helplines, allowing a facilitator to remotely verify ferment quality or pelletization technique and flag where refresher training is needed.
- Fund monitoring and evaluation of digital-traditional integration efforts on the same terms as other extension investments, so that the relative cost-effectiveness of different channel combinations (video versus radio versus SMS versus in-person) for natural farming specifically, rather than for agricultural extension in general, can be established.

Conclusion

The next generation of Indian agriculture is often framed around sensors, artificial intelligence and precision inputs. This chapter has argued for a complementary and, for the majority of India's smallholders, more immediately relevant reading of "smart farming": the intelligent use of digital tools to scale traditional, low-cost, ecologically grounded practices that already have a strong evidence base and a large and growing base of practising farmers. Bio-fertilizer preparations such as Jeevamrutham, seed treatment and pelletization protocols, and soil-cover and moisture-management practices together constitute a coherent, low-input production system; community radio, participatory video and mobile advisory together constitute a low-cost, high-reach extension system. Neither half of this pairing works as well alone as it does combined with peer-based, trust-driven community institutions of the kind pioneered in Andhra Pradesh's natural farming programme. Realising this potential at national scale will depend less on new technology than on sustained institutional commitment to producing verified content, training and supporting community-level facilitators, and integrating natural farming into the mobile and broadcast advisory channels farmers already use.

References

1. Bharucha, Z. P., Mitjans, S. B., & Pretty, J. (2020). Towards redesign at scale through zero budget natural farming in Andhra Pradesh, India. *International Journal of Agricultural Sustainability*, 18, 1–20.
2. Khadse, A., & Rosset, P. M. (2019). Zero budget natural farming in India: From inception to institutionalisation. *Agroecology and Sustainable Food Systems*, 43, 848–871.

3. Khadse, A., Rosset, P. M., Morales, H., & Ferguson, B. G. (2018). Taking agroecology to scale: The zero budget natural farming peasant movement in Karnataka, India. *Journal of Peasant Studies*, 45(2), 192–219.
4. Gandhi, R., Veeraraghavan, R., Toyama, K., & Ramprasad, V. (2009). Digital Green: Participatory video for agricultural extension. *Information Technologies & International Development*, 5(1), 1–15.
5. Kondylis, F., Mueller, V., & Zhu, J. (2017). Seeing is believing? Evidence from an extension network experiment. *Journal of Development Economics*, 125, 1–20.
6. Palekar, S. (2006). *The philosophy of spiritual farming*. Zero Budget Natural Farming Research, Development and Extension Movement, Amravati.
7. Government of Andhra Pradesh / Rythu Sadhikara Samstha. (2019). *Andhra Pradesh Community Managed Natural Farming: Concept note*. Rythu Sadhikara Samstha, Vijayawada.
8. Food and Agriculture Organization of the United Nations. (2021). *Zero Budget Natural Farming (ZBNF) in India*. FAO Agroecology Knowledge Hub. [https://www.fao.org/agroecology/in-action/detail/zero-budget-natural-farming-\(zbnf\)-in-india/en](https://www.fao.org/agroecology/in-action/detail/zero-budget-natural-farming-(zbnf)-in-india/en)
9. Department of Agriculture and Farmers Welfare, Government of India. (2020). *mKisan Portal and Kisan Call Centre – Digital agriculture extension services*. Ministry of Agriculture and Farmers Welfare. <https://mkisan.gov.in>
10. Digital Green. (2023). *Evidence review of Digital Green's video-mediated farmer extension approach*. Digital Green, New Delhi. <https://digitalgreen.org>
11. Abdul Latif Jameel Poverty Action Lab (J-PAL). (2018). *Video-based support for small-scale farmers around the world*. J-PAL Case Study. <https://www.povertyactionlab.org/case-study/video-based-support-small-scale-farmers-around-world>

WHOLE-GRAIN FOODS IN OBESITY MANAGEMENT: SATIETY, GUT MICROBIOTA, AND METABOLIC HEALTH

Nivetha Muralikrishnaa* and John Wyson

Department of Food Processing Technology,
AMET University, Chennai, Tamil Nadu, India

*Corresponding author E-mail: nivethakrishnaa20@gmail.com

Abstract

Obesity is a multifactorial metabolic disorder characterised by excessive adiposity, disrupted appetite regulation, insulin resistance and chronic low-grade inflammation. Improving carbohydrate quality through whole-grain consumption represents a practical dietary strategy for addressing these interconnected abnormalities. Whole grains retain the bran, germ and endosperm, providing dietary fibre, resistant starch, phenolic compounds, vitamins and minerals within an intact food matrix. This chapter evaluates how whole-grain foods may support obesity management through enhanced satiety, modulation of the gut microbiota and improvement of metabolic health. Soluble viscous fibres, particularly β -glucan from oats and barley, delay gastric emptying and nutrient absorption while potentially promoting satiety-related intestinal hormones. Fermentable fibres and resistant starch are metabolised by colonic microorganisms into short-chain fatty acids that can influence appetite, intestinal integrity, glucose metabolism and inflammatory signalling. Whole-grain foods may additionally reduce dietary energy density, improve insulin responsiveness and support favourable lipid regulation. Nevertheless, reductions in body weight are generally modest and differ according to grain species, food structure, processing intensity, intervention duration and baseline metabolic phenotype. Minimally processed oats, barley, rye, whole wheat, brown rice and millets may offer greater benefits than finely milled or sweetened products carrying whole-grain claims. Whole grains should therefore replace refined cereals within energy-appropriate dietary patterns rather than be added indiscriminately. Although not an independent treatment for obesity, structurally intact whole-grain foods can strengthen sustainable weight-management programmes by improving appetite control, microbial functionality and cardiometabolic resilience.

Keywords: Whole Grains, Obesity, Satiety, Gut Microbiota, Dietary Fibre, Metabolic Health.

1. Introduction

Obesity develops through complex interactions among energy imbalance, food quality, neuroendocrine appetite regulation, microbial dysbiosis, genetics and the surrounding food environment. Effective management therefore requires strategies that extend beyond calorie counting and promote lasting improvements in dietary quality and metabolic function. Whole-

grain foods are promising because they preserve the bran, germ and endosperm, delivering fibre, resistant starch, micronutrients and phytochemicals within a naturally organised matrix.

These structural and compositional characteristics can alter mastication, gastric emptying, nutrient digestion, intestinal fermentation and postprandial metabolism. Their effects may enhance fullness, reduce subsequent energy intake and support metabolic pathways disrupted in obesity. Nevertheless, the whole-grain designation does not ensure uniform physiological activity. Grain species, milling, extrusion, cooking and added ingredients can substantially modify satiety and glycaemic responses. This chapter examines how whole grains influence appetite regulation, gut microbial activity, adiposity and metabolic health, while critically considering their limitations and future role in personalised obesity management.

2. Whole Grain Structure and Satiety Regulation

Satiety is governed by interactions among gastric distension, nutrient sensing, intestinal hormones and central appetite pathways. Whole-grain foods may influence these systems through their fibre concentration, particle size, water-holding capacity and structural resistance to digestion. Coarse or intact kernels generally require greater mastication and remain in the gastrointestinal tract longer than finely milled cereals, potentially extending meal duration and perceived fullness.

Soluble β -glucan from oats and barley forms a viscous matrix following hydration. Increased gastrointestinal viscosity can delay gastric emptying, restrict enzymatic access to starch and moderate glucose absorption. A slower rate of nutrient delivery may prolong satiation while limiting rapid postprandial glucose and insulin fluctuations that can promote subsequent hunger. Oat β -glucan consumed at breakfast has been shown to reduce postprandial glycaemic exposure, although responses depend on dose, molecular weight and food formulation (Hossain *et al.*, 2025). Whole-grain proteins, resistant starch and fibre may also stimulate appetite-regulating peptides, including glucagon-like peptide-1 and peptide YY, while suppressing orexigenic signals such as ghrelin. However, direct evidence for consistent changes in food intake remains heterogeneous. Palatability, habitual diet and compensation during later meals can weaken short-term satiety effects. Whole grains should therefore be viewed as facilitators of energy control rather than direct appetite suppressants.

3. Gut Microbiota and the Whole Grain Obesity Axis

Whole grains provide diverse microbiota-accessible carbohydrates, including resistant starch, arabinoxylans, β -glucan and oligosaccharides. These components escape complete digestion in the small intestine and undergo colonic fermentation. Their utilisation can modify microbial composition and increase the production of acetate, propionate and butyrate. These short-chain fatty acids support epithelial integrity and interact with metabolic and immune pathways associated with adiposity.

Butyrate supplies energy to colonocytes and reinforces epithelial-barrier function. Propionate may influence hepatic glucose production, whereas acetate participates in peripheral energy metabolism. Short-chain fatty acids can also activate receptors associated with peptide YY and glucagon-like peptide-1 secretion, creating a plausible connection between microbial fermentation and appetite regulation. Whole-grain interventions have produced changes in particular microbial taxa and fermentation profiles, although substantial differences occur among individuals (Cui *et al.*, 2022).

Recent evidence indicates that the fibre source, kernel structure and baseline microbiome may be more important than total fibre alone. Oats, rye and barley provide different substrates and consequently generate distinct microbial responses (Comerford, 2026). A higher diet–gut microbiota index, reflecting greater consumption of microbiota-supportive foods, has also been associated with lower odds of obesity in adults (Huang *et al.*, 2025a).

Nevertheless, major microbiome changes are not universally observed following whole-grain interventions. Functional changes in metabolite production may occur without extensive alterations in taxonomic composition. The gut microbiota should consequently be understood as a potential mediator and response modifier rather than the sole explanation for whole-grain-associated weight regulation.

4. Effects on Body Weight and Adiposity

Observational studies generally associate greater whole-grain intake with lower body mass index, waist circumference and risk of central obesity. A recent population analysis reported that higher consumption was associated with reduced odds of both general and abdominal obesity, although residual confounding cannot be excluded (Wang *et al.*, 2024).

Intervention evidence is less uniform. Whole-grain diets can support modest reductions in body weight and fat mass, particularly when they replace refined grains within energy-controlled diets. A recent randomised trial among adults with obesity found that both 50- and 100-g daily whole-grain interventions reduced body weight and abdominal adiposity compared with a control diet. The lack of a clear difference between the two doses suggests that benefits may not increase linearly with consumption (Wang *et al.*, 2026).

Whole grains may influence adiposity by reducing dietary energy density, improving satiation and increasing faecal energy loss. Their fibre matrix can limit macronutrient bioaccessibility, while fermentation and improved insulin sensitivity may affect substrate utilisation. However, a whole-grain diet does not automatically create an energy deficit. Large portions, calorie-dense toppings and highly sweetened whole-grain products can offset potential advantages.

Weight reduction should not be regarded as the sole measure of effectiveness. Improvements in visceral fat, glycaemic variability, insulin resistance, lipids and inflammatory status may occur

even when changes in total body weight are limited. Whole-grain substitution may therefore improve metabolic health independently of dramatic weight loss.

5. Glucose, Lipid, and Inflammatory Regulation

Obesity frequently coexists with insulin resistance, dyslipidaemia, hepatic fat accumulation and chronic inflammation. Whole grains may address these abnormalities by slowing carbohydrate digestion and reducing postprandial glucose and insulin exposure. Meta-analytic evidence indicates that whole-grain consumption can improve glycaemic traits, although the magnitude varies among grain types and participant groups (Li *et al.*, 2023; Ying *et al.*, 2024).

Oat and barley β -glucan can reduce total and LDL cholesterol through increased intestinal viscosity and bile-acid excretion. Evidence also suggests improvements in lipid profiles following both whole-oat and isolated β -glucan interventions (Yu *et al.*, 2022; de Morais Junior *et al.*, 2023). These metabolic effects are important because obesity-associated insulin resistance and dyslipidaemia substantially increase cardiovascular risk.

Whole-grain phenolics may reduce oxidative stress and regulate pro-inflammatory pathways. Ferulic acid, avenanthramides, tocopherols and related compounds can potentially restrict inflammatory signalling, while microbiota-derived metabolites may reinforce intestinal-barrier integrity. Diets rich in fibre and antioxidant-containing plant foods could consequently reduce excessive activation of inflammatory complexes such as NLRP3 (van der Heiden & te Velde, 2026).

6. Practical Integration into Obesity Management

Whole grains should replace refined cereals rather than merely increase total food intake. Rolled or steel-cut oats, barley, rye, whole-wheat kernels, brown rice and minimally processed millets can replace white bread, polished rice and sweetened breakfast cereals. Combining them with pulses, vegetables and protein-rich foods may further enhance satiety and moderate meal-level glycaemic responses.

Product selection should consider physical structure, declared whole-grain content, fibre, added sugar, sodium and serving size. Highly extruded cereals, biscuits and sweetened granola should not be classified as metabolically favourable solely because they contain whole-grain flour. Gradual introduction and adequate hydration can reduce gastrointestinal discomfort. Most importantly, whole-grain consumption should be integrated with an appropriate energy deficit, physical activity, sleep management and behavioural support. Its primary contribution is to make weight-control diets more satiating, nutritionally adequate and metabolically protective.

7. Challenges and Future Perspectives

Whole-grain research must move beyond the assumption that every grain and every consumer respond identically. Trials differ in grain species, processing, dose, energy restriction and intervention duration, while satiety is often assessed using subjective scales. Microbiome

outcomes are equally heterogeneous and frequently lack functional metabolite measurements (Cui *et al.*, 2022). Future trials should combine continuous glucose monitoring, appetite hormones, objective food-intake assessment, body-composition imaging, faecal energy measurements and multi-omics analysis. Grain particle size, β -glucan molecular weight, resistant-starch content and polyphenol bioavailability should be reported systematically.

The most promising direction is precision whole-grain nutrition. Baseline microbiota, insulin resistance, appetite phenotype and cultural eating patterns could help predict whether an individual responds best to oats, barley, rye, wheat, brown rice or millets. Fermentation and controlled processing may further improve palatability and microbial accessibility without accelerating starch digestion (Huang *et al.*, 2025b). Future products should be affordable, convenient and clinically validated. The objective is not simply to add whole-grain ingredients, but to engineer satisfying foods that generate measurable improvements in appetite, adiposity and metabolic resilience.

Conclusion

Whole-grain foods offer a practical method for improving carbohydrate quality within comprehensive obesity management. Their retained bran, germ and endosperm provide viscous and fermentable fibres, resistant starch, phenolic compounds, vitamins and minerals in a structurally organised matrix. These properties can delay digestion, prolong gastric processing, support satiety signalling and reduce rapid postprandial metabolic fluctuations. Fermentation of cereal fibres additionally produces short-chain fatty acids capable of influencing intestinal integrity, appetite-related hormones, glucose metabolism and inflammatory regulation.

However, whole-grain consumption should not be presented as an independent weight-loss treatment. Evidence suggests that reductions in body weight and adiposity are generally modest and vary across individuals, foods and interventions. The strongest application is substitution: intact or minimally processed whole grains should replace refined cereals within a controlled-energy dietary pattern. Simply adding whole-grain products to an energy-surplus diet is unlikely to produce meaningful weight loss.

Metabolic benefits may also occur without substantial movement on the weighing scale. Improvements in visceral adiposity, insulin sensitivity, glycaemic stability, lipid regulation and inflammatory status remain clinically important outcomes. Accordingly, future interventions should evaluate body composition and metabolic health rather than relying exclusively on body mass index. Whole-grain recommendations must further distinguish intact kernels and coarse products from finely milled, highly extruded or sugar-rich foods. Preserving physical structure and fibre functionality is essential to maintaining their physiological value. Whole grains do not manage obesity by replacing discipline with fibre; they work by replacing refined foods with a more satiating, microbiota-accessible and metabolically intelligent food matrix.

References

1. Comerford, K. B. (2026). The impacts of ready-to-eat cereals and cereal fibers on gut health, body weight, and cardiometabolic health. *Frontiers in Nutrition*, 13, Article 1717345. <https://doi.org/10.3389/fnut.2026.1717345>
2. Cui, Z., Wu, S., Liu, Y., Liu, J., Zhang, H., & Li, Y. (2022). The effect of whole-grain diet on the gut microbiota of elderly individuals. *Frontiers in Nutrition*, 9, Article 919838. <https://doi.org/10.3389/fnut.2022.919838>
3. de Morais Junior, A. C., Venancio, V. P., Silva, L. B. A. R., & da Silva, B. P. (2023). The separate effects of whole oats and isolated beta-glucan on lipid profiles: A systematic review and meta-analysis of randomized controlled trials. *Clinical Nutrition ESPEN*, 53, 134–149. <https://doi.org/10.1016/j.clnesp.2022.12.011>
4. Guo, H., Wu, H., Sajid, A., & Li, Z. (2022). Whole-grain cereals: The potential roles of functional components in human health. *Critical Reviews in Food Science and Nutrition*, 62(30), 8388–8402. <https://doi.org/10.1080/10408398.2021.1928596>
5. Hossain, M. M., Tosh, S. M., Jovanovski, E., & Wolever, T. M. S. (2025). Oat beta-glucans consumed at breakfast improve glucose tolerance at a subsequent meal: A randomized crossover trial. *Food & Function*, 16, 5436–5447. <https://doi.org/10.1039/D5FO00353A>
6. Huang, H., Wu, H., Qiu, B., Zhang, Y., & Li, Z. (2025b). The impact of whole-grain consumption on metabolic health: Evidence, mechanisms and future perspectives. *Food & Function*. <https://doi.org/10.1039/D5FO03240G>
7. Huang, Y., Huang, H., Liu, Q., Zhang, Y., & Liu, Y. (2025a). The association between a newly proposed gut microbiota dietary index and obesity among U.S. adults: A cross-sectional analysis based on NHANES 1999–2020. *Nutrition Journal*, 24, Article 143. <https://doi.org/10.1186/s12937-025-01249-8>
8. Li, S., Zong, A., An, R., Wang, H., Liu, L., Liu, J., Guo, X., Xu, Z., Wang, J., Li, D., Du, F., & Xu, T. (2023). Effects of whole-grain intake on glycaemic traits: A systematic review and meta-analysis of randomized controlled trials. *Critical Reviews in Food Science and Nutrition*, 63(20), 4351–4370. <https://doi.org/10.1080/10408398.2021.2001429>
9. Llanaj, E., Ádány, R., Lachat, C., & D’Haese, M. (2022). Effect of oat supplementation interventions on cardiovascular disease risk markers: A systematic review and meta-analysis of randomized controlled trials. *European Journal of Nutrition*, 61(4), 1749–1778. <https://doi.org/10.1007/s00394-021-02763-1>
10. Madsen, M. T. B., Biloft-Jensen, A., Lassen, A. D., Tetens, I., & Kristensen, M. (2024). Effects of whole-grain compared with refined-grain intake on appetite and energy intake: A systematic review and meta-analysis of randomized controlled trials. *The American Journal of Clinical Nutrition*, 119(2), 410–425.

11. Nickel, D. V., Jannasch, F., & Schulze, M. B. (2026). Systematic review of diet-quality scores including diet diversity in relation to major chronic diseases, obesity and mortality in healthy adults. *European Journal of Nutrition*, 65, Article 125. <https://doi.org/10.1007/s00394-026-03907-x>
12. Ridwan, H., Ahmed, S., Singh, R. B., *et al.* (2026). Sustainable diets and functional foods for the prevention of cardiometabolic diseases and sustainable development goals of the UNO: An international consensus scientific statement. *BMC Cardiovascular Disorders*, 26, Article 569. <https://doi.org/10.1186/s12872-026-05557-7>
13. Sanders, L. M., Zhu, Y., Wilcox, M. L., Koecher, K., & Maki, K. C. (2023). Whole-grain intake, compared with refined-grain intake, improves postprandial glycaemia and insulinaemia: A systematic review and meta-analysis of randomized controlled trials. *Critical Reviews in Food Science and Nutrition*, 63(21), 5339–5357. <https://doi.org/10.1080/10408398.2021.2017838>
14. Sobota, A., Sobota, M., & Krysiak, O. (2026). Cereal-based functional foods in diabetes management: Nutritional quality, glycaemic response and health implications. *Applied Sciences*, 16(12), Article 6015. <https://doi.org/10.3390/app16126015>
15. Sun, H., Lee, P. H., Zhu, X., Chen, Y., & Wong, S. H. S. (2022). A randomized controlled trial of the effects of whole-grain versus refined-grain diets on the microbiome in pregnancy. *Scientific Reports*, 12, Article 7509. <https://doi.org/10.1038/s41598-022-11571>
16. van der Heiden, J. F., & te Velde, A. A. (2026). Balancing nutrition and inflammation: The role of a healthy diet in NLRP3 inflammasome activation. *Immuno*, 6(1), Article 13. <https://doi.org/10.3390/immuno6010013>
17. Wang, Y., Zhang, X., Li, Y., Huang, J., & Chen, G. (2024). Association between whole-grain intake and obesity defined by different anthropometric indicators among adults. *Nutrients*, 16(14), Article 2373. <https://doi.org/10.3390/nu16142373>
18. Wang, Y., Li, Y., Chen, Y., Zhang, X., Zhao, M., & Zhou, J. (2026). Effectiveness of whole grain on body weight and cardiometabolic risk in adults with obesity: A parallel randomised controlled trial. *Frontiers in Nutrition*, 13, Article 1774209. <https://doi.org/10.3389/fnut.2026.1774209>
19. Ying, T., Zheng, J., Kan, J., Li, W., Xue, K., Du, J., Liu, Y., & He, G. (2024). Effects of whole grains on glycaemic control: A systematic review and dose–response meta-analysis of prospective cohort studies and randomized controlled trials. *Nutrition Journal*, 23, Article 47. <https://doi.org/10.1186/s12937-024-00952-2>
20. Yu, J., Xia, J., Yang, C., Pan, D., Xu, D., Sun, G., & Wang, S. (2022). Effects of oat beta-glucan intake on lipid profiles in hypercholesterolemic adults: A systematic review and meta-analysis of randomized controlled trials. *Nutrients*, 14(10), Article 2043. <https://doi.org/10.3390/nu14102043>

DISEASE MANAGEMENT IN SESAME: AN INTEGRATED APPROACH

A. Chandini^{*1}, M.B.G.S. Kumari², A.B.M. Sirisha³ and Rohit Kumar⁴

¹Department of Plant Pathology, ARS, Yelamanchili-531055,

²Department of Agronomy,

³Department of GPBR,

⁴Department of Genetics and Plant Breeding,

ARS, Yelamanchili, Andhra Pradesh 531055

Corresponding author E-mail: chandiniampolu3@gmail.com, mbgs.kumari@angrau.ac.in,
abm.sirisha@ac.in, rohitrohit58171@gmail.com

Abstract

Sesame (*Sesamum indicum* L.) is one of the oldest cultivated oilseed crops and is valued worldwide for its high oil content, superior nutritional quality, natural antioxidants, and diverse food, pharmaceutical, and industrial applications. However, sesame productivity is constrained by several fungal, bacterial, and phytoplasma diseases that occur at different stages of crop growth and cause substantial losses in seed yield and quality. Important diseases include Alternaria leaf blight, Cercospora leaf spot, powdery mildew, charcoal rot, Fusarium wilt, stem and root rots, anthracnose, bacterial blight, and phyllody. These diseases can adversely affect plant growth, reduce photosynthetic efficiency, impair capsule development, and ultimately decrease seed yield and quality. Although chemical fungicides have traditionally been used for disease management because of their rapid and effective action, their indiscriminate and repeated use may result in environmental pollution, pesticide residues, development of pathogen resistance, and adverse effects on non-target organisms. Integrated Disease Management (IDM) provides a sustainable alternative by combining compatible management practices such as resistant cultivars, healthy seed, cultural and agronomic practices, biological control agents, botanicals, organic amendments, regular disease surveillance, and need-based application of selective fungicides. An integrated approach can reduce dependence on chemical inputs, enhance the effectiveness of biological control, improve soil and ecosystem health, and contribute to sustainable sesame production. This chapter provides an overview of the major diseases affecting sesame, their symptoms, epidemiology, economic importance, and integrated management strategies. It is intended to serve as a useful reference for students, researchers, extension professionals, and other stakeholders involved in sustainable sesame production and disease management.

Introduction

Sesame (*Sesamum indicum* L.) is one of the earliest domesticated oilseed crops, cultivated since ancient times for its high nutritional and economic value (Joshi, 1961; Weiss, 1983). Its seeds are

rich in oil and protein and are widely used for edible oil, food and value-added products, while sesame oil is valued for its oxidative stability due to lignans and antioxidants such as sesamin, sesamolin and sesamol, which also possess antioxidant and neuroprotective properties (Anilakumar *et al.*, 2010; Cheng *et al.*, 2006; Miyahara *et al.*, 2001). In India, sesame is grown during *kharif*, rabi and summer seasons across diverse agroecological regions, but productivity is often reduced by diseases such as *Alternaria* leaf spot/blight, powdery mildew, charcoal rot, *Fusarium* wilt, *Cercospora* leaf spot, anthracnose, bacterial blight and phyllody, which can adversely affect plant growth, capsule development, seed yield and quality. Although fungicides provide effective disease suppression, their repeated use may cause environmental contamination, pesticide residues and pathogen resistance. Hence, sustainable sesame disease management requires Integrated Disease Management (IDM), involving resistant cultivars, healthy seed, crop rotation, field sanitation, suitable sowing time and spacing, balanced nutrition, biological control, botanicals, organic amendments, disease monitoring and need-based fungicide application. The effectiveness and importance of integrated approaches have been reported for major sesame diseases, including *Alternaria* leaf spot, powdery mildew, *Cercospora* leaf spot, *Fusarium* wilt and charcoal rot (Gupta *et al.*, 2018; Kavak and Boydak, 2006; Palakshappa *et al.*, 2020; Prabhu *et al.*, 2018). Biological control agents suppress pathogens through competition, antibiosis, mycoparasitism and induction of host defence, while organic amendments and botanicals can enhance microbial activity and pathogen suppression. Therefore, integrating host resistance, cultural practices, biological control, botanicals, organic amendments, disease monitoring and judicious fungicide use offers a practical and sustainable strategy for reducing disease-associated losses and improving sesame productivity and resilience.

Diseases in Sesame

Sesame (*Sesamum indicum* L.) is affected by a remarkably diverse range of pathogens belonging to fungi, oomycetes, bacteria, phytoplasmas, viruses, and virus-like organisms throughout its cultivation worldwide. These diseases occur at different stages of crop growth, from seed germination to maturity, and infect virtually all plant parts, including roots, stems, leaves, flowers, capsules, and seeds. Table 1 summarizes the major diseases of sesame reported worldwide along with their associated causal pathogens.

Table 1: Diseases of sesame reported globally.

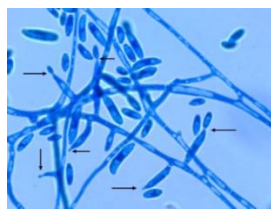
Disease	Causal Pathogen
A. Fungi	
Charcoal rot/Dry root rot	<i>Macrophomina phaseolina</i>
Wilts	<i>Fusarium oxysporum</i> f. sp. <i>sesame</i> / <i>Fusarium</i> spp., <i>Verticillium</i> spp., <i>Neocosmospora</i> spp.

Root rot/Stem rot	<i>Rhizoctonia solani</i> , <i>Sclerotinia</i> spp., <i>Phymatotrichopsis</i> spp., <i>Thielaviopsis</i> spp., <i>Helicobasidium</i> spp., <i>Gibberella</i> spp.
Root/stem/collar rot, southern blight	<i>Sclerotium rolfsii</i>
Alternaria leaf spot/leaf blight	<i>Alternaria sesame</i> / <i>A. alternata</i> / <i>A. simsimi</i> / <i>Alternaria</i> spp.
Cercospora leaf spot	<i>Cercospora sesame</i>
Angular leaf spot	<i>Cercospora sesamicola</i>
Powdery mildew	<i>Oidium</i> spp., <i>Podosphaera xanthii</i> (= <i>Sphaeroteca fuliginea</i>), <i>Leveillula taurica</i> / <i>Leveillula</i> spp., <i>Erysiphe cichoracearum</i> (syn. <i>Golovinomyces cichoracearum</i>) / <i>Erysiphe orontii</i> / <i>Erysiphe</i> spp., <i>Podosphaera</i> spp.
Corynespora blight and target spot	<i>Corynespora cassiicola</i>
Brown angular spot	<i>Cylindrosporium sesame</i> / <i>Pseudocercospora sesame</i>
Aerial stem rot/Leaf spot	<i>Helminthosporium sesame</i> / <i>Helminthosporium</i> spp.
Leaf spots	<i>Ascochyta</i> spp., <i>Cladosporium</i> spp., <i>Colletotrichum</i> spp., <i>Curvularia</i> spp., <i>Drechslera</i> spp., <i>Cercoseptoria</i> spp., <i>Cochliobolus</i> spp., <i>Gloeosporium</i> spp., <i>Exserohilum</i> spp., <i>Phoma</i> spp., <i>Pseudocercospora</i> spp., <i>Myrothecium</i> spp., <i>Paramyrothecium</i> spp., <i>Pestalotiopsis</i> spp.
Stem blight	<i>Didymella</i> spp.
Wet rot of seedlings	<i>Choanephora cucurbitarum</i>
Leaf blight	<i>Nigrospora sphaerica</i>
Anthracnose	<i>Colletotrichum</i> spp., <i>Sphaeronema</i> spp.
Rust/Warts	<i>Synchytrium</i> spp.
B. Oomycetes	
Phytophthora blight	<i>Phytophthora</i> spp.
Damping-off	<i>Pythium</i> spp.
C. Bacteria	
Bacterial leaf spot	<i>Pseudomonas</i> spp.
Bacterial blight	<i>Xanthomonas campestris</i> pv. <i>sesame</i> , <i>Pseudomonas solanacearum</i> = <i>Ralstonia solanacearum</i>
Bacterial wilt	<i>Erwinia</i> spp.
Phyllody, Witches' broom	Phytoplasma

Yellows	<i>Spiroplasma</i> spp.
Seed-borne disease	<i>Memnoniella</i> spp.
D. Viruses	
Mosaic	Cowpea Aphid-Borne Mosaic Virus (CABMV), Tobacco vein banding mosaic virus (TVBMV), Watermelon Mosaic Virus (WMV), Bean Common Mosaic Virus (BCMV), Zucchini yellow mosaic virus (ZYMV), Sesame yellow mosaic virus (YMo-I), Turnip mosaic virus (TuMV), Pepper mild mosaic virus (PMMoV), Tobacco mosaic virus (TMV)
Stripe	Peanut stripe virus (PSV)
Leaf curl	Sesame curly top virus (SeCTV), Tomato yellow leaf curl virus (TYLCV), Tobacco leaf curl virus (TLCV)
Spotted wilt	Tomato spotted wilt virus (TSWV)
Yellow spot	Melon yellow spot virus (MYSV)
Bud necrosis	Groundnut bud necrosis virus (GBNV)

Fusarium Wilt

Fusarium wilt of sesame, caused by *Fusarium oxysporum* f. sp. *sesami*, is a destructive soil- and seed-borne disease occurring from the seedling stage to crop maturity and causing substantial yield losses under favourable disease conditions (Gupta *et al.*, 2018; Alemaw *et al.*, 1997). The pathogen colonizes the vascular tissues of roots and stems, interfering with water and nutrient transport and ultimately causing irreversible wilting (Ara, 2017). The disease is widely distributed in major sesame-growing regions, where infected fields commonly show characteristic patches of wilted and dead plants (Anon., 2025; Joshi *et al.*, 2012; Kavak and Boydak, 2006). Symptoms initially develop as yellowing of older leaves, followed by drooping, loss of turgidity, progressive wilting, premature drying and eventual plant death, while infected roots and stems show diagnostic dark brown to black vascular discoloration resulting from fungal invasion and necrosis (Anon., 2025). The pathogen survives adverse conditions mainly through thick-walled chlamydospores that persist in soil and infected crop residues for three to six years, contributing to long-term disease persistence (Dita *et al.*, 2018; Leslie and Summerell, 2008; Stover, 1962). Primary infection may arise from infected seed or germinating chlamydospores in soil, whereas secondary dissemination occurs through conidia carried by rain splash and irrigation water (Anon., 2025). Under severe epidemics, particularly in susceptible genotypes, Fusarium wilt can result in yield losses of up to 100%, making it one of the most economically important diseases limiting sesame production (Mahdy *et al.*, 2022).



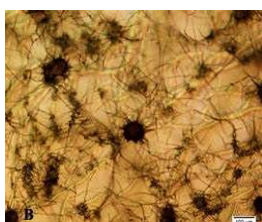
Micro, Macro conidia



Wilting of plants

Charcoal Rot (Dry Root Rot)

Charcoal rot or dry root rot of sesame, caused by *Macrophomina phaseolina* (Tassi) Goid. (syn. *Rhizoctonia bataticola*), is a destructive soil-borne disease widely distributed across sesame-growing regions and is particularly severe under hot and dry conditions, with yield losses ranging from about 5% to complete crop failure depending on environmental conditions, cultivar susceptibility and inoculum density (Verma *et al.*, 2005; Maiti *et al.*, 1988; Meena *et al.*, 2018; Rajput *et al.*, 2021). The pathogen attacks sesame from seedling emergence to maturity, causing damping-off in young plants, while older plants exhibit lower-leaf yellowing, drooping, wilting, premature defoliation, dark brown to black collar lesions, stem girdling, bark shredding and eventual plant death; infected roots become dry and brittle and contain numerous black microsclerotia, while pycnidia may develop on stems, capsules and seeds, sometimes causing premature capsule splitting and shrivelled, discoloured seeds (Vikaspedia, 2021; Anon., 2025; Maiti *et al.*, 1988). The pathogen survives for several years mainly as microsclerotia in soil, crop residues and infected seed, with pycnidia also contributing to survival (Anon., 2025). Disease severity is also positively associated with soil inoculum density, and increasing pathogen populations can cause substantial reductions in sesame yield (El-Bramawy, 2006; Suja *et al.*, 2020).



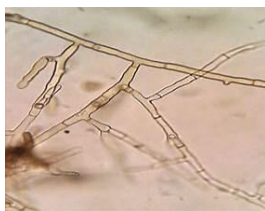
Microsclerotial bodies



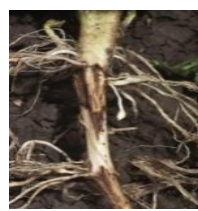
Drooping, Wilting and rotting of roots

Root Rot, Stem Rot, Seedling Blight, and Damping-off

Root rot, stem rot, seedling blight, and damping-off of sesame are caused by *Rhizoctonia solani* and are recognized as important diseases in several sesame-growing regions, including Australia (Verma *et al.*, 2005). The pathogen primarily attacks germinating seeds and young seedlings, resulting in poor crop establishment. Infected seedlings develop water-soaked lesions near the collar region, followed by tissue decay, collapse, and eventual death, leading to pre- and post-emergence damping-off. In older plants, the disease manifests as dark brown lesions on the stem just above the soil surface. As the infection progresses, necrosis extends upward along the stem, resulting in stunted growth, premature lodging, and significant yield reduction.



Sclerotium formation



Brown, Sunken and rotten roots

Effective management of damping-off requires an integrated disease management approach. Seed treatment with suitable fungicides or biological agents enhances seed germination and seedling vigour, thereby reducing early infection. The cultivation of resistant or tolerant cultivars, adoption of crop rotation, maintenance of optimum field sanitation, and implementation of integrated pest management practices help minimize disease incidence. Timely application of fungicides, biofungicides, or biological control agents during the early stages of crop growth further reduces disease development and improves plant establishment

Collar Rot, Southern Blight, and Stem/Root Rot

Collar rot, southern blight, and stem/root rot of sesame are caused by *Sclerotium rolfsii*, an important soil-borne pathogen widely distributed in tropical and subtropical regions (Verma *et al.*, 2005). The disease is characterized by yellowing of foliage, followed by wilting and drying of the entire plant. Infected plants develop brown, rotted lesions around the collar region, and abundant white mycelial growth accompanied by mustard seed-like brown sclerotia is observed on infected tissues and the adjacent soil surface (Eslami *et al.*, 2015). Severe infections result in extensive root decay, plant collapse, and considerable yield losses. Several management strategies have been reported for controlling *S. rolfsii*. Laboratory studies demonstrated that propiconazole (Tilt 250 EC) effectively inhibits the radial growth of the pathogen. Biological and organic management practices, including the application of *Trichoderma harzianum*, Nimbicidin, cow urine combined with vermiwash, and cow urine mixed with buttermilk, have also shown significant suppression of mycelial growth and sclerotial production. In addition, the incorporation of vermicompost into the soil has been reported to reduce disease incidence by improving soil microbial activity and suppressing pathogen survival (Shamsi and Naher, 2020; Praveenkumar, 2009).



Mycelium development



Brown sclerotial bodies with white mycelium

Alternaria Leaf Spot, Leaf Blight, and Stem Necrosis

Alternaria diseases are among the most prevalent foliar diseases of sesame and are caused by several species of *Alternaria*. Alternaria leaf spot is primarily caused by *Alternaria sesami* and *A. simsimi*, whereas Alternaria leaf blight is caused by *Alternaria alternata* (Verma *et al.*, 2005; Naik *et al.*, 2017; Ojiambo *et al.*, 1999; Ojiambo *et al.*, 1998; Prakash, 2007; Ramamohana Rao and Vijayalakshmi, 2000; Sahu and Verma, 2016; Choi *et al.*, 2014; Nayyar *et al.*, 2017). The disease affects all aerial parts of the plant throughout the crop growth period and may substantially reduce seed yield and quality under favourable environmental conditions. Symptoms initially appear as small, circular to irregular, dark brown, water-soaked lesions on leaves. As the disease progresses, the lesions enlarge and develop characteristic concentric rings, giving them a typical target-board appearance. Under conditions of prolonged high humidity and frequent rainfall, lesions coalesce to form extensive blighted areas, leading to premature defoliation. Similar lesions may also occur on petioles, stems, midribs, veins, and capsules. Severe infections result in stem necrosis, extensive leaf blight, poor capsule development, and occasionally complete plant death. The pathogen survives on infected crop residues, contaminated seeds, and soil, serving as the primary source of inoculum in subsequent cropping seasons. Disease development is favoured by temperatures ranging from 20 to 30°C, prolonged cloudy weather, and high atmospheric humidity. Sesame plants are particularly susceptible during the 8–10-week growth stage, when favourable environmental conditions accelerate pathogen multiplication and disease spread (Ojiambo *et al.*, 1999). Since *Alternaria* species possess a broad host range, infected crop residues and alternate hosts play an important role in disease epidemiology (Ojiambo *et al.*, 2003; Rotem, 1994). Several *Alternaria* species have been isolated from sesame seed. Yu *et al.* (1982) identified *Alternaria sesami*, *A. sesamicola*, *A. alternata*, and *A. longissima* from sesame seed samples collected in Korea. Among these, *A. sesamicola* was the predominant seed-borne species. Although *A. longissima* has generally been regarded as a saprophyte, it was subsequently confirmed to be pathogenic, causing zonate leaf spots, foliage blight, stem necrosis, and capsule infection. Both *A. sesami* and *A. sesamicola* significantly reduced seed germination and seedling establishment (Yu *et al.*, 1982).



Transverse and longitudinal conidia



**Dark brown irregular water soaked lesions
on leaves**

Cercospora Leaf Spot

Cercospora leaf spot, caused by *Cercospora sesami* Zimm., is one of the most important and widely distributed foliar diseases of sesame throughout the major sesame-growing regions of the world (Verma *et al.*, 2005; TNAU Agritech, 2015). The disease attacks sesame throughout its growth period and infects all above-ground plant parts, including leaves, petioles, stems, and capsules, often resulting in severe defoliation, poor capsule development, and significant reductions in seed yield (Londase, 2013). Initial symptoms usually appear about four weeks after sowing as minute, pale brown to whitish spots on the leaves. These lesions gradually enlarge into circular to irregular spots measuring approximately 5–15 mm in diameter, with greyish centres surrounded by dark brown margins. Under prolonged periods of high humidity and frequent rainfall, individual lesions coalesce to form large necrotic patches, leading to extensive leaf blight, premature defoliation, and damage to developing capsules (Anon., *Diseases of Sesamum*; Tamil Nadu Agricultural University, 2021). The pathogen is both externally and internally seed-borne and is also capable of surviving on infected crop residues, which serve as important primary sources of inoculum in subsequent cropping seasons (Tamil Nadu Agricultural University, 2021). Secondary spread occurs through wind-dispersed conidia, rain splash, and irrigation water. Disease development is favoured by warm temperatures, prolonged leaf wetness, frequent rainfall, and high relative humidity, conditions that promote spore germination, infection, and rapid disease spread (Teshome *et al.*, 2022).



Conidiophore



Circular brown spots with yellow halo

Angular Leaf Spot (Brown Angular Spot)

Angular leaf spot, also referred to as brown angular spot, is caused by *Pseudocercospora sesami*, previously known under the synonyms *Cercospora sesamicola*, *Cercoseptoria sesami*, and *Cylindrosporium sesami* (Min and Toyota, 2019; Verma *et al.*, 2005; EPPO, 2002). The disease is an important seed-borne foliar disease of sesame and occurs from the seedling stage until crop maturity. The pathogen survives on infected seed and crop debris, serving as a primary source of inoculum for subsequent cropping seasons (Palakshappa *et al.*, 2020). Symptoms first appear as small, angular, brown lesions measuring approximately 2–3 mm in diameter. The lesions typically possess grey to ash-coloured centres with dark brown margins and are characteristically delimited by the leaf veins, giving them an angular appearance (TNAU Agritech, 2015; Palakshappa *et al.*, 2020). Under favourable environmental conditions, lesions enlarge and coalesce, resulting in extensive blighting and premature defoliation. The pathogen also infects

petioles, stems, and capsules, producing elongated, dark, sunken lesions that adversely affect capsule development and seed production.



Conidia



Ash coloured centers with dark brown margins

Powdery Mildew

Powdery mildew is an economically important foliar disease of sesame occurring in most sesame-growing regions and is caused by several fungi, including *Erysiphe cichoracearum*, *E. orontii*, *Leveillula taurica*, *Oidium erysiphoides*, *O. sesami*, *O. mirabilifolii*, *Podosphaera xanthii* (syn. *Sphaerotheca fuliginea*) and *Sphaerotheca fuliginea* (Verma *et al.*, 2005; Reddy and Haripriya, 1990; Rajpurohit, 1993; Patel *et al.*, 1949; Venkatakrishnaiya, 1958; Puzari *et al.*, 2006; Srinivasulu *et al.*, 2003; Gemawat and Verma, 1972). Because these pathogens have similar morphological features, molecular identification based on internal transcribed spacer (ITS) sequences is useful for species confirmation (Chen *et al.*, 2008), while cross-inoculation studies indicate considerable host specificity, as sesame powdery mildew pathogens did not infect sunflower (Sujatha *et al.*, 2015). The disease may reduce seed yield by 25–50%, with losses of about 45% reported under severe outbreaks in Uganda (Egonyu *et al.*, 2005), and *Oidium erysiphoides* is among the common causal fungi, infecting sesame from seedling to maturity (Verma *et al.*, 2005; Venkata *et al.*, 2013). Symptoms occur mainly on leaves but may also affect stems, petioles, buds, flowers and capsules, initially appearing as small white powdery patches that enlarge and coalesce, followed by chlorosis, necrosis, curling and premature defoliation; severe infection can impair flower and capsule development and produce shrivelled seeds (Venkata *et al.*, 2013). *Podosphaera xanthii* (syn. *Sphaerotheca fuliginea*) has also been reported from India and commonly develops during flowering and post-flowering under high humidity, cool nights and moderate daytime temperatures, causing substantial reductions in capsule formation and yield (Sujatha *et al.*, 2015; Venkata *et al.*, 2013). *Leveillula taurica* primarily infects the leaf lamina, producing yellow chlorotic spots on the upper surface corresponding to white fungal growth on the lower surface, which later enlarges, becomes necrotic and may cause premature leaf fall (PlantwisePlus Knowledge Bank, 2021). *Erysiphe cichoracearum* produces greyish-white powdery colonies on leaves that may spread to flowers and young capsules, resulting in flower drop, malformed leaves, premature defoliation and poor capsule development; at advanced stages, cleistothecia give the growth a grey to black

appearance, and the fungus survives on infected debris, with airborne ascospores initiating primary infection and wind-dispersed conidia facilitating secondary spread (Anon., *Diseases of Sesamum*). Disease development is favoured by moderate temperatures and alternating dry and humid conditions, while management includes removal of infected residues, field sanitation and timely application of wettable sulphur or dinocap (Karathane), which are effective under field conditions (Rajpurohit, 1993).



Conidia germination on leaf



White powdery mycelial mass on leaves

Corynespora Blight (Target Spot)

Corynespora blight, also known as target spot, is caused by *Corynespora cassiicola* and is recognized as one of the important foliar diseases of sesame in several sesame-growing regions. The pathogen has a broad host range and survives in infected crop residues, soil, and seed for extended periods, thereby serving as a persistent source of primary inoculum (Snow & Berggren, 1989; Meena *et al.*, 2011; Mmbaga *et al.*, 2018). Formation of chlamydospores enables the pathogen to withstand adverse environmental conditions and contributes to disease recurrence in successive cropping seasons (Dixon *et al.*, 2009; Adorada *et al.*, 2024). The disease is characterized by circular to irregular target-like lesions with concentric rings and dark brown centres on leaves. Under favourable environmental conditions, lesions enlarge and coalesce, leading to extensive leaf blighting, premature defoliation, and reduction in photosynthetic area. Similar lesions also develop on petioles, stems, and capsules, while severe infections may extend to the root system, resulting in root rot (Smith *et al.*, 1988; Adorada *et al.*, 2024). Disease development is favoured by warm temperatures, prolonged leaf wetness, high relative humidity, and dense crop canopies that retain moisture for longer periods (Adorada *et al.*, 2024).



Obclavate conidia with truncate base



Circular to irregular target-like lesions

Other Minor Fungal Diseases of Sesame

Besides the major diseases, several fungal pathogens infect sesame, although their economic importance varies depending on geographical location and environmental conditions.

Anthracnose, caused by *Colletotrichum* spp., produces dark brown lesions surrounded by yellow halos on leaves, stems, and capsules. As infection progresses, lesions enlarge and develop black acervuli on infected tissues. The disease is favoured by warm and humid weather and spreads through rain splash, irrigation water, insects, and contaminated farm implements. Although generally considered a minor disease, localized outbreaks may occur under favourable environmental conditions (Kolte, 1985; AICRP Sesame and Niger, 2023; Adorada *et al.*, 2024).

Minor Leaf Spots of Sesame



Anthracnose

Bipolaris

Helminthosporium

Ascochyta blight



Cladosporium

Choanephora

Phytophthora blight

Pythium

Bipolaris leaf spot, caused by *Bipolaris sorokiniana*, is characterized by small brown to purplish lesions that gradually enlarge into irregular reddish-brown patches. Severe infections result in premature leaf drying and reduced photosynthetic efficiency. Information regarding its epidemiology and management in sesame remains limited (Adorada *et al.*, 2024).

Helminthosporium leaf spot (Brown leaf spot), caused by *Helminthosporium sesami*, produces small circular dark brown lesions that later develop greyish-white centres. The pathogen infects leaves, stems, petioles, capsules, and seeds, leading to reductions in both seed yield and oil quality. Infected seed also serves as an important source of inoculum for subsequent cropping seasons (Kolte, 1985; AICRP Sesame and Niger, 2023; Adorada *et al.*, 2024).

Ascochyta blight, caused by *Ascochyta sesami*, often resembles *Alternaria* and *Cercospora* leaf spots during the early stages of infection. The disease produces elongated lesions on stems and circular spots on leaves and capsules bearing numerous pycnidia. The pathogen survives in infected seed and crop residues, and disease development is favoured by cool, humid weather. Integrated management includes crop rotation, destruction of infected residues, use of certified disease-free seed, resistant cultivars where available, seed treatment, timely fungicide applications, and strict field sanitation because spores are easily disseminated through machinery, workers, and animals (McDonald *et al.*, 2018; Adorada *et al.*, 2024).

Cladosporium leaf spot, caused by *Cladosporium* spp., produces small circular tan lesions with characteristic dark green sporulation at advanced stages. Several seed-borne species have been associated with poor seed germination, although their pathogenic significance in sesame requires further investigation. Copper-based fungicides may provide protection when disease pressure is high (Ellis, 1971; Adorada *et al.*, 2024).

Wet rot of seedlings, caused by *Choanephora cucurbitarum*, primarily affects young seedlings under hot and humid conditions. Infection generally begins on wounded tissues, producing water-soaked lesions that rapidly become soft and necrotic before being covered with greyish-brown fungal growth. High soil moisture, poor drainage, and elevated humidity strongly favour disease development (Agrios, 2005; Adorada *et al.*, 2024).

Phytophthora blight, caused by *Phytophthora parasitica* var. *sesami*, infects sesame throughout all growth stages. Initial symptoms include water-soaked lesions on leaves and stems that later become dark brown to black. Severe infections result in root decay, premature defoliation, blighting, shrivelled seeds, and plant death. The pathogen survives in soil as dormant mycelium and oospores, while infected seed also serves as a source of primary inoculum. Disease development is favoured by poorly drained soils, prolonged rainfall, temperatures around 25°C, and relative humidity exceeding 90%. Effective management includes seed treatment with captan or thiram, crop rotation, destruction of infected residues, improved drainage, and timely application of metalaxyl-based fungicides. Resistant genotypes identified through breeding programmes also provide opportunities for long-term disease management (Kolte, 1985; Rao *et al.*, 1994; Sharma *et al.*, 2012; Adorada *et al.*, 2024).

Damping-off, commonly caused by *Pythium aphanidermatum* and *Pythium ultimum*, results in poor seed germination and seedling mortality. The disease is favoured by excessive soil moisture, poor drainage, over-irrigation, high soluble salt concentrations, and root injuries. Infected seedlings exhibit root decay, chlorosis, stunted growth, and eventual collapse. Management includes improving soil drainage, avoiding excessive irrigation, practising crop rotation, using healthy seed, and adopting appropriate seed treatment measures to minimize soil-borne inoculum (Agrios, 2005; Adorada *et al.*, 2024).

Bacterial and Phytoplasma Diseases of Sesame

Bacterial Blight

Bacterial blight, caused by *Xanthomonas campestris* pv. *sesami*, is an important seed-borne disease of sesame that affects plants at all growth stages and contributes significantly to disease dissemination through infected seed (Maiti *et al.*, 1988; Edward *et al.*, 2022). The disease initially appears as small water-soaked lesions on the lower surface of leaves, which later become visible on the upper surface. As infection progresses, the lesions enlarge, become angular due to vein restriction, and turn dark brown. Under severe infection, adjacent lesions

coalesce to form large necrotic patches, resulting in extensive leaf blight and premature drying. Reddish-brown elongated lesions may also develop on petioles and stems (Kolte, 1985; Edward *et al.*, 2022). The bacterium is a Gram-negative, motile rod possessing a single polar flagellum and survives in infected crop debris and contaminated seed. Secondary spread primarily occurs through rain splash and irrigation water (Narayanasamy, 2011).



Gram negative, rod shape, Purple stain

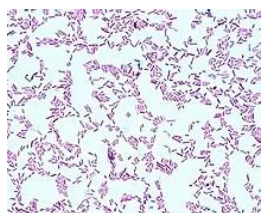


Angular leaf due to vein restriction

Bacterial Leaf Spot

Bacterial leaf spot is caused by *Pseudomonas sesami* or *Pseudomonas syringae* pv. *sesami* and has been reported from several sesame-growing regions (Maiti *et al.*, 1988; Edward *et al.*, 2022). Initial symptoms appear as minute water-soaked yellow specks on the upper leaf surface that gradually enlarge into angular brown lesions delimited by veins. Under humid conditions, bacterial exudates may appear as shiny droplets on infected tissues. Severe infection leads to extensive leaf spotting, blighting, and premature defoliation (Kolte, 1985).

The pathogen survives internally in infected seed and diseased plant debris and is disseminated mainly through rain splash, irrigation water, and strong winds. Laboratory studies have shown that hot water seed treatment and streptomycin seed soaking significantly reduce seed-borne infection and improve germination, while foliar applications of antibiotics effectively suppress disease development (Narayanasamy, 2011; Edward *et al.*, 2022).



Gram negative, rod shape, Purple stain



Yellow specks on upper leaf surface

Phyllody: Phyllody is one of the most destructive diseases of sesame and is caused by a phytoplasma belonging to '*Candidatus Phytoplasma*'. The pathogen is confined to the phloem tissues and lacks a true cell wall. It is transmitted mainly by leafhopper vectors and survives in numerous cultivated and weed hosts that serve as reservoirs of infection (Akhtar *et al.*, 2009; Edward *et al.*, 2022). Disease symptoms begin with the transformation of floral organs into green leafy structures, accompanied by prominent vein clearing and excessive proliferation of shoots. As infection advances, flowers are completely replaced by malformed leaves, internodes become shortened, and profuse branching gives the plant a characteristic "witches' broom" appearance. Infected plants produce either malformed capsules or fail to set seed altogether, resulting in yield

losses that may exceed 90% under severe epidemics (Maiti *et al.*, 1988; Akhtar *et al.*, 2009). The phytoplasma survives in alternate hosts such as chickpea, groundnut, rapeseed, mustard, clover, and several weed species. Leafhopper populations increase during warm seasons, enhancing disease transmission. The incubation period varies with both the insect vector and the host plant, influencing disease development in the field (Narayanasamy, 2011; Edward *et al.*, 2022).

Viral Diseases

Compared with fungal, bacterial, and phytoplasma diseases, viral diseases have been reported less frequently in sesame. However, several viruses including sesame mosaic virus, cucumber mosaic virus, and tobacco streak virus have been documented in different sesame-growing countries, causing symptoms such as mosaic mottling, chlorosis, leaf distortion, stunting, and reduced capsule development (Brunt *et al.*, 1996; Edward *et al.*, 2022).

Most sesame viruses are transmitted by insect vectors, including aphids and thrips, while some are also seed- or mechanically transmitted. Disease development is greatly influenced by vector abundance, environmental conditions, and the availability of alternate host plants (Hull, 2014).

Integrated Disease Management of Sesame

Integrated disease management (IDM) provides a sustainable strategy for reducing losses caused by fungal, bacterial, phytoplasma and viral diseases of sesame, particularly because major pathogens such as *Macrophomina phaseolina*, *Fusarium oxysporum* f. sp. *sesami*, *Rhizoctonia solani*, *Sclerotium rolfsii* and *Xanthomonas campestris* pv. *sesami* are soil- and seed-borne (Maiti *et al.*, 1988; Gupta *et al.*, 2018). The use of certified disease-free seed and appropriate seed treatment with carbendazim, thiram, captan or carbendazim + thiram is an important first-line measure for reducing primary inoculum and improving seedling establishment (Maiti *et al.*, 1988; Gupta *et al.*, 2018; TNAU Agritech Portal, 2015). Cultural practices such as 2–3-year rotation with non-host crops, deep summer ploughing, removal of infected residues, optimum spacing, balanced fertilization, proper irrigation and avoidance of waterlogging reduce pathogen survival and disease development (Kolte, 1985; Gupta *et al.*, 2018; Lamichhane *et al.*, 2017). Biological control using *Trichoderma viride*, *T. harzianum*, *Pseudomonas fluorescens* and *Bacillus subtilis*, particularly when combined with farmyard manure or vermicompost, suppresses soil-borne pathogens through competition, mycoparasitism, antibiosis and induction of host resistance while promoting plant growth (Praveenkumar, 2009; Palakshappa *et al.*, 2020; Gupta *et al.*, 2018). Foliar diseases such as *Alternaria* and *Cercospora* leaf spots, *Corynespora* blight and powdery mildew can be managed through timely and need-based application of fungicides such as mancozeb, chlorothalonil, propiconazole, hexaconazole, difenoconazole and wettable sulphur (Rajpurohit, 1993; Teshome and Kora, 2021; Palakshappa *et al.*, 2020), whereas bacterial diseases are primarily controlled through healthy seed, sanitation, crop rotation, residue destruction, avoidance of overhead irrigation and, where permitted, appropriate

antibiotic seed or foliar treatments (Narayanasamy, 2011; Verma *et al.*, 2005). Management of phyllody and viral diseases depends mainly on removal of infected plants, elimination of alternate weed hosts, vector management and cultivation of tolerant cultivars, with intercropping and neem-based insecticides also contributing to vector suppression (Akhtar *et al.*, 2009; Rao and Nabi, 2015). Host resistance remains an economical and environmentally safer component, and resistant or moderately resistant sesame genotypes against charcoal rot, Fusarium wilt, powdery mildew and phyllody can be incorporated into breeding programmes (Kavak and Boydak, 2006; Gopal *et al.*, 2005; Gupta *et al.*, 2018). Thus, integrating healthy seed, resistant cultivars, cultural practices, biological control, balanced nutrition, vector management, disease monitoring and judicious chemical application provides a practical and sustainable approach for managing major sesame diseases.

Host Resistance and Future Perspectives

The development of resistant cultivars remains the most sustainable strategy for long-term management of charcoal rot. Although resistant sources have not yet been identified under Indian conditions, several sesame genotypes exhibiting moderate resistance or tolerance have been reported from other sesame-growing countries and are being utilized in resistance breeding programmes (Zhang *et al.*, 2020).

Recent advances in transcriptomic studies have considerably improved the understanding of host resistance mechanisms against *M. phaseolina*. Comparative analyses between resistant and susceptible sesame genotypes have identified several defence-related genes involved in pathogen recognition, oxidative stress responses, and activation of systemic defence pathways, providing valuable molecular resources for future resistance breeding programmes (Zhang *et al.*, 2020; Wei *et al.*, 2021; Li *et al.*, 2023).

References

1. Adorada, D.L., Poudel, B., Shivas, R.G., Barbetti, M.J., Kelly, L.A., Sparks, A.H. and Tan, Y.P. (2024) 'Diseases of sesame in Australia: Current status, emerging pathogens and future challenges', *Australasian Plant Pathology*.
2. Agrios, G.N. (2005) *Plant Pathology*. 5th edn. Burlington, Massachusetts: Elsevier Academic Press, 922 p.
3. AICRP Sesame and Niger (2023) *Annual Progress Report (2022–23)*. Jabalpur, India: All India Coordinated Research Project on Sesame and Niger, Indian Council of Agricultural Research, JNKVV.
4. Alemaw, G., Terefe, G., Zewdie, K. and Weyesa, B. (1997) *Lowland Oilcrops: A Three-Decade Research Experience in Ethiopia*. Research Report No. 31. Addis Ababa, Ethiopia: Ethiopian Institute of Agricultural Research.

5. Anilakumar, K.R., Pal, A., Khanum, F. and Bawa, A.S. (2010) 'Nutritional, medicinal and industrial uses of sesame (*Sesamum indicum* L.) seeds—an overview', *Agricultural Conspectus Scientificus*, 75, pp. 159–168.
6. Ara, A. (2017) 'Histopathological studies of sesame (*Sesamum indicum*) seedlings infected with *Fusarium oxysporum*', *Plant Pathology Quarterly*, 7, pp. 82–90.
7. Brunt, A.A., Crabtree, K., Dallwitz, M.J., Gibbs, A.J. and Watson, L. (1996) *Viruses of Plants: Descriptions and Lists from the VIDE Database*. Wallingford, UK: CAB International.
8. Chen, R.S., Chu, C., Cheng, W., Chen, W.Y. and Tsay, J.G. (2008) 'Differentiation of two powdery mildews of sunflower (*Helianthus annuus*) by a PCR-mediated method based on ITS sequences', *European Journal of Plant Pathology*, 121, pp. 1–8.
9. Cheng, F.C., Jinn, T.R., Hou, R.C.W. and Tzen, J.T.C. (2006) 'Neuroprotective effects of sesamin and sesamol on gerbil brain in cerebral ischemia', *International Journal of Biomedical Science*, 2, pp. 284–288.
10. Choi, Y.P., Paul, N.C., Lee, H.B. and Yu, S.H. (2014) 'First record of *Alternaria simsii* causing leaf spot on sesame (*Sesamum indicum* L.) in Korea', *Mycobiology*, 42, pp. 405–408.
11. Dita, M., Barquero, M., Heck, D., Mizubuti, E.S.G. and Staver, C.P. (2018) 'Fusarium wilt of banana: Current knowledge on epidemiology and research needs toward sustainable disease management', *Frontiers in Plant Science*, 9, 1468.
12. Dixon, L.J., Schlub, R.L., Pernezny, K. and Datnoff, L.E. (2009) 'Host specialization and phylogenetic diversity of *Corynespora cassiicola*', *Phytopathology*, 99, pp. 1015–1027.
13. Edward, M., Tadesse, A., Fenta, B. and Hailu, G. (2022) 'Diseases of sesame and their integrated management: A review', *Journal of Biology, Agriculture and Healthcare*, 12(8), pp. 1–15.
14. EPPO (2021) '*Pseudocercospora sesami*', *EPPO Global Database*.
15. Eslami, A., Khodaparast, S.A., Mousanejad, S. and Dehkaei, F.P. (2015) 'Evaluation of the virulence of *Sclerotium rolfsii* isolates on *Arachis hypogaea* and screening for resistant genotypes under greenhouse conditions', *Hellenic Plant Protection Journal*, 8, pp. 1–11.
16. Gemawat, P.D. and Verma, O.P. (1972) 'A new powdery mildew of sesame (*Sesamum indicum*) incited by *Sphaerotheca fuliginea*', *Indian Journal of Mycology and Plant Pathology*, 2, p. 94.
17. Gupta, K., Naik, K. and Bisen, R. (2018) 'Status of sesame diseases and their integrated management using indigenous practices', *International Journal of Chemical Studies*, 6, pp. 1945–1952.
18. Hull, R. (2014) *Plant Virology*. 5th edn. London: Academic Press.

19. Joshi, A.B. (1961) *Sesamum: A Monograph*. Hyderabad: Indian Central Oilseeds Committee.
20. Joshi, M., Srivastava, R., Sharma, A.K. and Prakash, A. (2012) 'Screening of resistant varieties and antagonistic *Fusarium oxysporum* for biocontrol of Fusarium wilt of chilli', *Journal of Plant Pathology and Microbiology*, 3, pp. 1–6.
21. Kavak, H. and Boydak, E. (2006) 'Screening of sesame breeding lines for resistance to Fusarium wilt disease', *Plant Pathology Journal*, 5, pp. 157–160.
22. Kolte, S.J. (1985) 'Diseases of edible oil seed crops', in *Rapeseed-Mustard and Sesame Diseases*. Boca Raton, USA: CRC Press.
23. Leslie, J.F. and Summerell, B.A. (2008) *The Fusarium Laboratory Manual*. Ames, Iowa: Blackwell Publishing.
24. Li, X., Wang, H., Zhang, Y., Liu, J. and Zhao, Q. (2023) 'Comparative transcriptome analysis reveals defence-related genes associated with charcoal rot resistance in sesame', *BMC Plant Biology*, 23, 412.
25. Londase, S.B. (2013) *Studies on Cercospora leaf spot of sesame (Sesamum indicum L.)*. M.Sc. (Agriculture) thesis. Vasantrao Naik Marathwada Krishi Vidyapeeth, Parbhani, India.
26. Mahdy, R., Gaber, D.A., Hashem, M., Alamri, S. and Mahdy, E.E. (2022) 'Improving sesame (*Sesamum indicum* L.) seed yield through selection under infection of *Fusarium oxysporum* f. sp. *sesami*', *Plants*, 11, 1538.
27. Maiti, S., Kundu, A.B., Sen, S.P. and Acharya, S. (1988) *Sesame*. New Delhi: National Book Trust.
28. Meena, B., Rani, I., Meena, P.D. and Sharma, P. (2011) 'Corynespora leaf spot: An emerging disease and its management', *Plant Disease Research*, 26, pp. 95–101.
29. Meena, M., Gupta, S.K., Swapnil, P., Zehra, A., Dubey, M.K., Upadhyay, R.S. *et al.* (2018) '*Macrophomina phaseolina*: Current status and future prospects', *Journal of Plant Pathology*, 100, pp. 1–19.
30. Min, Y.J. and Toyota, K. (2019) 'Taxonomic reassessment of *Pseudocercospora sesami*', *Mycobiology*, 47(3), pp. 243–250.
31. Miyahara, Y., Hibasami, H., Katsuzaki, H., Imai, K. and Komiya, T. (2001) 'Sesamolin from sesame seed inhibits proliferation by inducing apoptosis in human lymphoid leukemia Molt 4B cells', *International Journal of Molecular Medicine*, 7, pp. 369–371. doi:10.3892/ijmm.7.4.369.
32. Mmbaga, M.T., Mrema, E. and Mortensen, C.N. (2018) 'First report of *Corynespora cassiicola* causing target spot on sesame', *Plant Disease*, 102, p. 2043.

33. Naik, M., Chennappa, G., Amaresh, Y.S., Sudha, S., Chowdappa, P. and Patil, S. (2017) 'Characterization of phytotoxin producing *Alternaria* species isolated from sesame leaves and their toxicity', *Indian Journal of Experimental Biology*, 55, pp. 36–43.
34. Narayanasamy, P. (2011) *Microbial Plant Pathogens: Detection and Disease Diagnosis—Bacterial and Phytoplasmal Pathogens*. Dordrecht, The Netherlands: Springer.
35. Nayyar, B.G., Woodward, S., Mur, L.A.J., Akram, A., Arshad, M., Naqvi, S.M.S. and Akhund, S. (2017) 'Incidence of *Alternaria* species associated with infected sesame seeds from Punjab, Pakistan', *Plant Pathology Journal*, 33, pp. 543–550.
36. Ojiambo, P.S., Ayiecho, P.O. and Nyabundi, J.O. (1999) 'Severity of *Alternaria* leaf spot and seed infection by *Alternaria sesami* as affected by plant age of sesame', *Journal of Phytopathology*, 147, pp. 403–407.
37. Ojiambo, P.S., Mibey, R.K., Narla, R.D. and Ayiecho, P.O. (2003) 'Field transmission efficiency of *Alternaria sesami* in sesame from infected seed', *Crop Protection*, 22, pp. 1107–1115.
38. Ojiambo, P.S., Narla, R.D., Ayiecho, P.O. and Nyabundi, J.O. (1998) 'Effect of infection level of sesame seed by *Alternaria sesami* on severity of *Alternaria* leaf spot', *Tropical Agricultural Research and Extension*, 1, pp. 125–130.
39. Palakshappa, M., Banu, H., Patil, L. and Vanishree, C.J.K. (2020) 'Biopriming and integrated management of *Cercospora* leaf spot of sesame caused by *Cercospora sesamicola*', *Journal of Pharmacognosy and Phytochemistry*, 9, pp. 3130–3133.
40. Patel, M.K., Kamat, M.N. and Bhide, V.P. (1949) 'Fungi of Bombay Supplement I', *Indian Phytopathology*, 2, pp. 142–155.
41. PlantwisePlus Knowledge Bank (2021) '*Leveillula taurica* (Powdery mildew)'. Wallingford, UK: CABI.
42. Prabhu, H.V., Channappa, G., Amaresh, Y.S. and Patil, S. (2018) 'Integrated management of charcoal rot of sesame caused by *Macrophomina phaseolina*', *International Journal of Current Microbiology and Applied Sciences*, 7(9), pp. 1514–1520.
43. Prakash, V.R.N. (2007) *Alternaria leaf spot of sesame caused by Alternaria sesami*. APS Publication No. IW000081.
44. Praveenkumar, N. (2009) *Studies on Biological Management of Collar Rot of Sesame Caused by Sclerotium rolfsii Sacc.* M.Sc. (Ag.) thesis. University of Agricultural Sciences, Dharwad, India.
45. Puzari, K.C., Sarbhoy, A.K., Ahmad, N. and Agarwal, D.K. (2006) 'New species of powdery mildews from North Eastern Region of India', *Indian Phytopathology*, 59, pp. 72–79.

46. Rajpurohit, T. (1993) 'Occurrence, varietal reaction and chemical control of powdery mildew of sesame', *Indian Journal of Mycology and Plant Pathology*, 23, pp. 207–209.
47. Ramamohana Rao, N. and Vijayalakshmi, M. (2000) 'Studies on *Alternaria sesami* pathogenic to sesame', *Microbiological Research*, 155, pp. 129–131.
48. Reddy, C.D.R. and Haripriya, S. (1990) 'Heterosis for tolerance to powdery mildew in sesame', *Indian Journal of Mycology and Plant Pathology*, 20, pp. 160–161.
49. Rotem, J. (1994) *The Genus Alternaria: Biology, Epidemiology and Pathogenicity*. St. Paul, Minnesota: American Phytopathological Society.
50. Sahu, U. and Verma, K. (2016) 'Isolation, identification and pathogenicity of *Alternaria sesami* causing leaf spot of sesame', *Annals of Plant and Soil Research*, 18, pp. 86–87.
51. Sarr, M.P., Ndiaye, M., Groenewald, J.Z. and Crous, P.W. (2014) 'Genetic diversity of *Macrophomina phaseolina* and evaluation of fungicides against charcoal rot', *Crop Protection*, 59, pp. 31–37.
52. Shamsi, S. and Naher, N. (2020) 'In vitro management of *Sclerotium rolfsii*, the causal agent of stem rot of sesame', *International Journal of Bioinformatics and Biological Sciences*, 8, pp. 1–6.
53. Shivas, R.G., Brockway, C.A. and Beilharz, V.C. (1996) 'First record in Australia of *Cercospora sesami* and *Pseudocercospora sesami*', *Australasian Plant Pathology*, 25, p. 212.
54. Snow, S.K. and Berggren, G.T. (1989) 'Target spot of sesame caused by *Corynespora cassiicola*', *Plant Disease*, 73, pp. 938–940.
55. Srinivas, P., Rao, M.S., Reddy, P.N. and Reddy, K.R. (2019) 'Biological management of charcoal rot of sesame using *Trichoderma* spp.', *Journal of Pharmacognosy and Phytochemistry*, 8(4), pp. 1848–1852.
56. Stover, R.H. (1962) 'Studies on Fusarium wilt of bananas. VIII. Differentiation of clones by cultural interaction and volatile substances', *Canadian Journal of Botany*, 40, pp. 1467–1471.
57. Sujatha, M., Soni, P. and Jatothu, J. (2015) 'Identification of *Podosphaera xanthii* causing powdery mildew on sesame', *Journal of Oilseeds Research*, 32, pp. 183–185.
58. Tamil Nadu Agricultural University (2021) *Sesame Diseases*. Department of Plant Pathology. Coimbatore, India: Tamil Nadu Agricultural University.
59. Teshome, E. and Kora, D. (2021) 'Field evaluation of fungicides against *Cercospora* leaf spot of sesame', *Acta Entomology and Zoology*, 2, pp. 102–107.
60. Teshome, E., Kor, D., Hasen, T. and Merga, H. (2022) 'Cercospora leaf spot occurrence in sesame-growing districts of Ethiopia', *Academic Letters*, 4564.

61. Venkata, R.R.P., Anuradha, G., Prasuna, K., Gouri, S.V. and Siddiq, E.A. (2013) 'Inheritance of powdery mildew resistance in sesame—A review', *International Journal of Bio-resource and Stress Management*, 4, pp. 614–619.
62. Venkatakrishnaiya, N.S. (1958) 'Powdery mildew: Some new hosts in Mysore', *Mysore Agricultural Journal*, 33, pp. 5–6.
63. Verma, M., Mehta, N. and Sangwan, M. (2005) 'Fungal and bacterial diseases of sesame', in Saharan, G.S., Mehta, N. and Sangwan, M.S. (eds.) *Diseases of Oilseed Crops*. New Delhi: Indus Publishing Company, pp. 269–303.
64. Wei, X., Yan, W., Liu, X., Ni, Y., Zhao, H. and Tian, B. (2021) 'Comparative transcriptome analysis reveals molecular mechanisms of sesame resistance against *Macrophomina phaseolina*', *BMC Plant Biology*, 21, 159.
65. Weiss, W.A. (1983) *Caster, Sesame, Safflower*. London: Leonard Hill.
66. Yu, S.H., Mathur, S. and Neergaard, P. (1982) 'Taxonomy and pathogenicity of four seed-borne *Alternaria* species from sesame', *Transactions of the British Mycological Society*, 78, pp. 447–458.
67. Zhang, H., Li, Y., Wang, X., Wei, X. and Tian, B. (2020) 'Identification of charcoal rot-resistant sesame germplasm and molecular mechanisms of resistance', *Plant Disease*, 104, pp. 2874–2883.

IAA PRODUCING MICROORGANISMS: BIOSYNTHESIS, DETECTION, MECHANISMS OF ACTION, AND APPLICATIONS IN SUSTAINABLE AGRICULTURE

V. S. Patil

Department of Microbiology,

Lal Bahadur Shastri College of Arts, Science and Commerce, Satara-415002, M.S., India.

Corresponding author E-mail: vishwasp15@yahoo.com

Abstract

A rich diversity of microorganisms continuously interacts with higher plants in soil ecosystem and influences the development of plant root in the soil. Potential to exploit beneficial plant-microbe interactions to enhance plant growth and nutrient uptake has been well documented with microbial inoculant having enhanced plant growth promoting potential. This plant growth promoting microorganisms improve plant growth and soil quality by different mechanisms, including production of phyto-hormones. Indole-3-acetic acid (IAA) is a hormone that influences plant growth significantly. This book chapter emphasizes an overview on introduction to IAA, biosynthetic pathways of IAA, mechanisms of action of IAA, qualitative and quantitative detection of IAA, diversity of microorganisms producing IAA, and significance of IAA producing microorganisms in sustainable agriculture.

Keywords: Sustainable Agriculture, Biofertilizers, Phyto-Hormone, Indole-3-Acetic Acid.

1. Introduction

Auxins and ethylene are the two plant hormones that play an important role in root system development and finally their yield. Among these, auxin is the first hormone identified in 1880 by Charles Darwin. Indole-3-acetic acid (IAA) production is a common natural auxin produced by plants and also by several microorganisms that stimulate and facilitate plant growth. IAA is a plant growth hormone and is one of the most physiologically active auxins. IAA influences many physiological and biochemical reactions in plants. IAA producing microorganisms play a central role in plant growth regulation and development (Spaepen *et al.*, 2007).

2. Biosynthesis of IAA

IAA is a secondary metabolite synthesized from Tryptophan by many Tryptophan dependant and Tryptophan independent pathways in plants and many bacteria (Carreno-Lopez *et al.*, 2000) Matsukawa *et al.*, 2007). In bacteria there are several pathways of IAA biosynthesis, however two are most common (Fig.1). In Trp dependant pathway, tryptophan is converted to indole 3-acetamide (IAM) by tryptophan-2-monooxygenase and IAM is metabolized to IAA by IAM-hydrolase (Matsukawa *et al.*, 2007). Horemans and Vlassak (1985) demonstrated that

Azospirillum brasilense could produce IAA in the absence of tryptophan when grown aerobically showed that the highest levels of auxin were produced in the presence of NH_4 . It appears to be of particular importance during embryogenesis, when fine control over low levels of IAA is critical to polar development. Trp-independent pathway might contribute significantly to the newly synthesized IAA; however, extensive Trp-to-IAA conversion also occurs in such preparations.

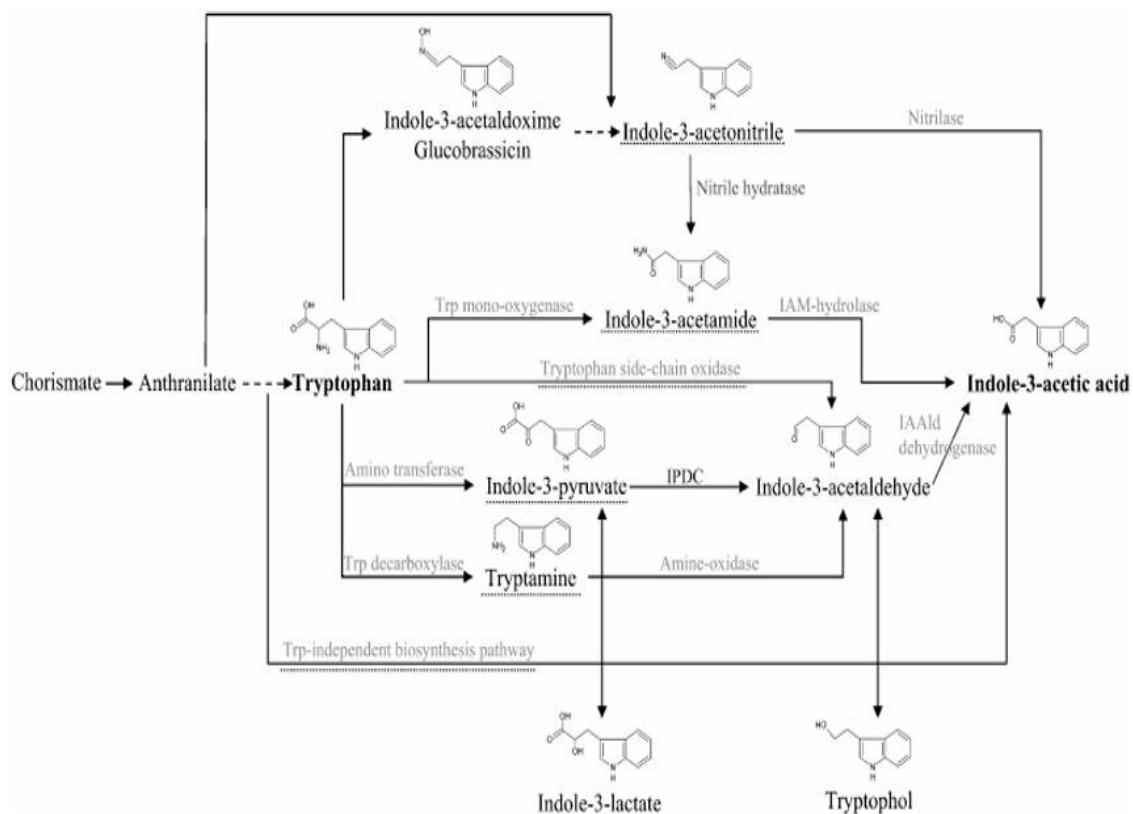


Figure 1: Biosynthesis of IAA in bacteria (Source: Spaepen *et al.*, 2007)

3. Mechanism of Action of IAA in Plant Growth Promotion

IAA is one of the most physiologically active auxins and plays an important role in plant growth and development. IAA stimulates root proliferation resulting in the production of longer roots with increased number of root hairs and root laterals which are involved in nutrient uptake (Spaepen *et al.*, 2007; Persello-Cartiaux *et al.*, 2003). In wheat, *Azospirillum brasilense* of wheat seedlings increases the number and length of lateral roots (Barbieri *et al.*, 1986). Further, it influences a range of cellular and physiological process, such as cell division, cell enlargement, tissue differentiation, bud dormancy, flowering, fruit ripening, seed dormancy, seed germination and leaf abscission and responses to light and gravity (Zhao, 2010; Teale *et al.*, 2006).

4. Detection of IAA Production Ability in Microbial Isolates

4.1 Qualitative Detection of IAA Production

The screening of microbial isolates for their ability to produce IAA is usually done by inoculating the microbial growth into 20 mL of nutrient broth tubes supplemented with 0.2 % (w/v) of L-tryptophan and incubated for 10 days at 28°C. The culture was centrifuged at 3,000

rpm for 20 min. The one mL supernatant was mixed with 2 mL of Salkowski reagent and tubes were incubated in dark for 30 min. The development of the red color was observed as the indication for positive result (Rahman *et al.*, 2010; Gordon and Weber, 1951) Uninoculated growth medium was used as negative control (Fig. 2).

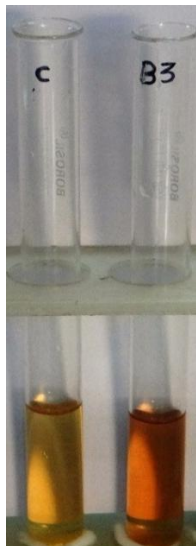


Figure 2: Blank (yellow colour) and positive test (red colour) indicating IAA production



Figure 3: Thin layer chromatographic separation of bacterially synthesized IAA (Source: Mohite, 2013)

For confirmation of IAA, the aliquots of centrifuged culture broth were extracted with ethyl acetate in 1:2 proportions. The organic phase was subjected to dryness by concentration and then diluted with 0.5 ml methanol. This sample along with the standard IAA was applied on silica gel plate and TLC was run by using a solvent system propanol: water (8:2) proportion and developed by using Salkowaski reagent (Chung *et al.*, 2003). The confirmation was achieved by comparing extracted sample with standard IAA on TLC. The pink coloured spots were observed on TLC plate at the Rf value 0.9 similar to the standard IAA (Fig.3).

4.2 Quantitative Estimation of IAA Production

The quantitative estimation of IAA is done by inoculating the suspension of IAA positive isolates into 200 mL of nutrient broth supplemented with 0.2 % (w/v) of L-tryptophan and incubated for 10 days at 28°C. The cell free extract was collected by centrifugation at 3,000 rpm for 20 min. The one mL supernatant was mixed with 2 mL of Salkowski reagent and tubes were incubated in dark for 30 minutes (Rahman *et al.*, 2010; Gordon and Weber, 1951). The mixture was then analyzed using spectrophotometer at 535 nm. The concentration of IAA in each sample was determined using a standard curve of IAA.

There are variations in the quantity of IAA produced by microorganisms in liquid broth and depends on the type of microbial species, strain, growth medium, L-tryptophan concentration, incubation time, pH, temperature, and type of analytical method used. Bacteria are reported to

produce typical quantity of IAA as 10-100 mg/L whereas high yielding bacterial strains are reported to produce 100-400 mg/L. Yeast members are reported to produce typical quantity of IAA as 5-50 mg/L whereas high yielding yeast strains are reported to produce 100-200 mg/L. Members belonging to molds are reported to produce typical quantity of IAA as 20-100 mg/L whereas high yielding mold strains are reported to produce 200-500 mg/L. Algae are reported to produce typical quantity of IAA as 1-30 mg/L whereas high yielding mold strains are reported to produce 30-100 mg/L.

5. Examples of IAA Producing Microorganisms

Biosynthesis of IAA is not limited to higher plants. Diverse soil microorganisms including bacteria, actinomycetes, yeasts, molds and algae are capable of producing IAA (Stein *et al.*, 1985; Muller *et al.*, 1989; Swain *et al.*, 2007; Pattern and Glick, 2002; Costacurta, and Vanderleyden, 1995). Production of IAA by microbial isolates varies greatly among different species and strains and depends on the availability of substrate(s).

Among soil microorganisms, bacteria that colonizes rhizosphere and plant roots and living freely in soil are able to produce IAA and are called as PGPR (Pattern and Glick, 2002). These bacteria have been isolated previously from soil and rhizosphere by several researchers (Harikrishnan *et al.*, 2014; Pant and Agrawal, 2014). Among these organisms various species of bacteria of genera *Pseudomonas*, *Xanthomonas*, *Azospirillum*, *Azotobacter*, *Rhizobium*, *Mesorhizobium*, *Klebsiella*, *Enterobacter*, *Acetobacter*, *Alcaligenes*, *Arthrobacter*, *Burkholderia*, *Bacillus* and *Serratia* have been reported to enhance the plant growth (Munees and Mohammad, 2001; Swain *et al.*, 2007). Reetha *et al.* (2014) reported *Pseudomonas fluorescens* and *Bacillus subtilis* isolated from rhizosphere of Onion produced IAA. Fluorescent *Pseudomonads* are considered to be the most promising group of plant growth promoting rhizobacteria involved in biocontrol of plant diseases (Moeinzadeh *et al.*, 2010). Combined application of a *P. fluorescens* along with *Bradyrhizobium* in groundnut significantly enhanced groundnut root and shoot dry weight, nodule number, nodule dry weight, and per cent nitrogen content of shoot (Vikram *et al.*, 2007). *Klebsiella pneumoniae* from rhizosphere of wheat is also reported to be efficient IAA producer (Sachdev *et al.*, 2009). *Micrococcus* strain NII-0909 isolated from Western Ghat forest possessed multiple plant growth traits including IAA (Dastager *et al.*, 2010). *B. subtilis* isolates improved the germination, emergence; increased root growth and nodulation in groundnut along with consistent colonization were reported by Turner and Backman (1991). Tsavkelova *et al.* (2006) stated that *Bacillus* involves the modulation of plant development through the production of phytohormones. Thus, several *Bacillus* species are capable of producing auxin that might stimulate root proliferation and nutrient uptake (Spaepen *et al.*, 2007). Members from Actinomycetes are also reported to be IAA producing and influencing plant growth. *Streptomyces spp.* isolated from some Thai medicinal plant rhizosphere soils is reported to be IAA producer (Khamna *et al.*, 2010). Study performed by Harikrishnan *et al.* (2014) shows 65

out of 95 Actinomycetes isolates from rice rhizosphere were found to be producing IAA and *Streptomyces spp* VSMGT1014 was found to be most potent having good potential as inoculants for the growth of rice seedlings.

The fungal members are also reported to be efficient IAA producers. *Pisolithus tinctorius*, *Suillus variegatus*, *Suillus granulatus*, *Aspergillus niger* strain BHUAS01, *Penicillium citrinum* strain BHUPC01 and *Trichoderma harzianum* (Yadav et al., 2013). Soil application of *Aspergillus awamori* and *P. fluorescens* separately increased the dry weight of shoot and this was found to be associated with IAA production ability (Khan et al., 2003).

IAA producing plant growth promoting yeasts have been isolated from rhizosphere, phyllosphere, and endosphere and their role in plant growth by promoting root elongation, seedling vigor and stress tolerance (especially drought, oxidative stress, low pH tolerance and heat stress) have been investigated (Amprayn et al., 2012; Deng et al., 2012; Fernandez-San Millan et al., 2022). The key IAA producing yeast members include *Saccharomyces cerevisiae*, *Rhodotorula mucilaginosa*, *Rhodotorula glutinis*, *Candida tropicalis*, *Candida ceilingensis*, *Pichia kudriavzevii*, *Meyerozyma guilliermondii*, etc (Nakamura et al., 1991; Xin et al., 2009; Limtong and Koowadjanakul, 2012; Aswiny et al., 2023).

Several algae from both Microalgae and Macroalgae group are reported to be producing IAA. IAA produced play important role in algal growth and can also promote plant growth when the algal biomass is used as biofertilizers or biostimulants (Martini et al., 2021; Limons et al., 2024; Goncalves et al., 2025; Muhammad et al., 2026). The algal genera most consistently reported for IAA production includes *Chlorella*, *Scenedesmus*, *Chlamydomonas*, *Nostoc*, *Anabaena*, *Oscillatoria*, *Sargassum*, *Kappaphycus*, *Gracilaria*, etc. IAA producing algae have potential application to be used in sustainable agriculture as they stimulate seed germination, promote root development, increase nutrient absorption and photosynthetic efficiency, and improve crop growth under abiotic stress conditions (Cerruti et al., 2024; Kumar et al., 2022; Supraja and Behera, 2020).

6. Role of IAA Producing Microorganisms in Sustainable Development Goals (SDGs)

The use of IAA producing microorganisms as biofertilizer in agriculture can contribute directly or indirectly to meet several United Nations Sustainable Development Goals (SDGs) as explained below.

SDG 2: Zero Hunger

IAA producing microorganisms has important contribution to sustainable crop production and to maintain food security. These microorganisms enhance seed germination and seedling establishment, stimulate root and shoot development, increase nutrient and water uptake, improve crop biomass and yield, and enhance plant tolerance to environmental stresses and thus can support SDG 2 (Zero Hunger) by contributing to productive and resilient crop systems.

SDG 3: Good Health and Well-being

The excess and inappropriate use of agrochemicals has resulted into environmental contamination including negative health impacts in human and animals. The use of IAA producing microorganisms has potential as biological alternatives to agrochemicals and thus can reduce dependency of agriculture sector on chemical fertilizers and pesticides, thereby minimizing human exposure to toxic residues in food and drinking water that meets SDG 3(Good Health and Well-being).

SDG 6: Clean Water and Sanitation

Agricultural runoff containing excessive nitrogen, phosphorus and agrochemicals is a major source of eutrophication that affects water quality and aquatic ecosystems. The use of these IAA producing microorganisms as bioinoculum in nutrient management strategies may help to reduce excessive fertilizer application and nutrient losses and prevention of eutrophication of waterbodies that meets SDG 6(Clean Water and Sanitation).

SDG 8: Decent Work and Economic Growth

The development and commercialization of IAA producing microorganisms as bioinoculum can stimulate the biofertilizer and agricultural biotechnology sector. The manufacturing of microbial biofertilizers, biostimulants and microbial consortia can generate opportunities for entrepreneurship, biotechnology industries and sustainable farming enterprises.

SDG 9: Industry, Innovation and Infrastructure

IAA producing microorganisms as biofertilizer offer considerable opportunities for innovation in agricultural biotechnology. Further research on IAA biosynthesis in microorganisms, strain improvement, fermentation conditions for large scale production and field application can lead to improved biofertilizer technologies which will serve as integral component of sustainable agricultural technologies.

SDG 12: Responsible Consumption and Production

The use of IAA producing microorganisms improves plant growth and there is enhanced nutrient uptake without directly supplying large quantities of agrochemicals. Thus, these microbial inoculants may reduce the requirement for chemical fertilizers and pesticides and foster ecofriendly farming practices.

SDG 13: Climate Action

The use of chemical fertilizers in agriculture sector contribute to greenhouse gas emissions. The use of IAA producing microorganisms as a biofertilizer and biostimulants can potentially reduce the requirement of synthetic fertilizer and contributing for significant reduction in release of greenhouse gases that will help to protect climate.

SDG14: Life Below Water

The use of IAA producing microorganisms as microbial inoculum in agriculture reduces the use of chemical fertilizers significantly. This results in reduction of agricultural nutrient pollution of neighbouring waterbodies preventing its eutrophication and protecting the life below water.

SDG 15: Life on Land

The use of IAA producing microorganisms as microbial inoculum in agriculture reduces the use of chemical fertilizers and pesticides and thus reduces pressure of these agrochemicals on soil and land ecology. Further, this results in supporting soil biological activity, soil fertility, increased microbial diversity and conservation of terrestrial ecosystem from degradation. In this way, IAA producing microorganisms can contribute significantly this SDG.

7. Significance of IAA Producing Microorganisms in Sustainable Agriculture

IAA producing microorganisms promote plant growth by direct mechanisms. IAA producing microorganisms promote rapid seed germination by stimulating cell division and elongation that causes improved seed vigor and hence seedlings emerge faster. IAA is reported to improve root system architecture that results in primary and lateral root elongation, root branching and increased root surface area that results in better nutrient absorption, improved draught tolerance and strong anchorage potential. Use of IAA bioinoculants will help to reduce the dependence on chemical fertilizer requirements so that further degradation of agriculture sector due to excess and abuse of chemical fertilizers will be prevented. Replacing chemical fertilizers with IAA producer bioinoculants reduces environmental pollution by preventing nitrate leaching, phosphate runoff, eutrophication of lentic water bodies and soil contamination that helps to protect ecosystems and water resources.

The potent microbial isolates with multiple PGPR traits can be used to prepare commercial biofertilizers to improve crop growth and reduce reliance on chemical inputs. The inoculation with IAA bioinoculants is reported to enhance crop productivity by increasing chlorophyll content, photosynthetic capacity, increased biomass accumulation and increased flower production and grain yield that finally enhances the agricultural productivity. IAA-producing microorganisms are reported to enhance plant tolerance to various abiotic stresses like drought, salinity, lower and higher temperature, and heavy metal stress. Many of the IAA-producing microorganisms possess additional PGPR traits like N₂ fixation, phosphate and or Potassium solubilization, Siderophore production, ACC deaminase production, HCN production, etc. that gives multiple benefits simultaneously to the inoculated plants. These bioinoculants frequently suppress many plant diseases by inhibiting pathogenes with the help of various direct and indirect mechanisms like producing antibiotics, siderophores, hydrolytic enzymes, and competing for the nutrients. IAA producing microorganisms have potential in climate resilient agriculture by improving stress tolerance, enhancing water use efficiency, and increasing nutrient

use efficiency under adverse conditions. All these abilities make them valuable components of organic farming, sustainable agriculture, and regenerative agriculture. The IAA producing microorganisms have a great potential to contribute directly or indirectly to achieve several SDGs.

8. Future Perspectives

IAA producing microorganisms from rhizosphere have extensive applications in sustainable agriculture so as to meet increasing food demand of growing population and environmentally friendly crop production. The isolation, cultivation and development of multifunctional individual and microbial consortia combining IAA production trait with other PGPR traits like nitrogen fixation, phosphate solubilization, ACC deaminase activity, and biocontrol traits offers significant potential for improving crop productivity under changing climatic conditions and stress conditions as well. Further research studies on these IAA producing microorganism using synthetic biology, microbiome engineering, genome editing, nanotechnology-based bioformulations, precision agriculture, and artificial intelligence-assisted strain selection will help to improve crop yield and functioning in stress conditions. Further studies on optimization conditions for formulation built up, long-term field evaluations, and region-specific bioinoculant development will further allow widespread use of these microorganisms in sustainable agriculture.

Conclusion

IAA producing microorganisms significantly contribute to sustainable agricultural systems by influencing positively crop productivity while reducing dependence on synthetic agrochemicals. With increasing concerns about soil degradation, environmental pollution, climate change, and the abuse of chemical fertilizers, IAA producing microorganisms have emerged as ecofriendly bioinoculants capable of improving plant growth, nutrient use efficiency, stress tolerance, and soil health. The integration of IAA producing microorganisms in sustainable agriculture directly advances several UN Sustainable Development Goals by replacing chemical fertilizers with these natural biological mechanisms and protecting agriculture, environment and health of all living beings. Continued research into their biology, mechanisms of action, formulation technologies, and field performance will strengthen their role in ensuring global food security along with environmental conservation, economic viability, and maintaining long term soil fertility.

References

1. Amprayn, K. O., Rose, M. T., Kecskes, M., Pereg, L., Nguyen, H. T., & Kennedy, I. R. (2012). Plant growth promoting characteristics of soil yeast (*Candida tropicalis* HY) and its effectiveness for promoting rice growth. *Applied Soil Ecology*, 61, 295–299.

2. Aswiny, N., Aiyanathan, E., Yesuraja, I., Chandramani, P., & Subhashini, R. (2023). Growth promoting trait of yeasts isolated from tomato in relation to IAA production. *International Journal of Environment and Climate Change*, 13(10), 2186–2196. <https://doi.org/10.9734/IJECC/2023/v13i102880>
3. Barbieri, P., Zanelli, T., Galli, E., & Zanetti, G. (1986). Wheat inoculation with *Azospirillum brasilense* Sp6 and some mutants altered in nitrogen fixation and indole-3-acetic acid production. *FEMS Microbiology Letters*, 36, 87–90.
4. Carreno-Lopez, R., Campos-Reales, N., Elmerich, C., & Baca, B. E. (2000). Physiological evidence for differently regulated tryptophan-dependent pathways for indole-3-acetic acid synthesis in *Azospirillum brasilense*. *Molecular and General Genetics*, 264, 521–530.
5. Cerruti, P., Campobenedetto, C., Montrucchio, E., Agliassa, C., Contartese, V., Acquadro, A., & Berteà, C. M. (2024). Antioxidant activity and comparative RNA-seq analysis support mitigating effects of an algae-based biostimulant on drought stress in tomato plants. *Physiologia Plantarum*, 176(6), e70007.
6. Chung, K. R., Shilts, T., Erturk, U., Timmer, L. W., & Uenq, P. P. (2003). Indole derivatives produced by the fungus *Colletotrichum acutatum* causing lime anthracnose and post bloom fruit drop of citrus. *FEMS Microbiology Letters*, 226(1), 23–30.
7. Dastager, S. G., Deepa, C. K., & Pandey, A. (2010). Isolation and characterization of novel plant growth promoting *Micrococcus* sp. NII-0909 and its interaction with cowpea. *Plant Physiology and Biochemistry*, 48(12), 987–992.
8. Deng, Z., Wang, W., Tan, H., & Cao, L. (2012). Characterization of heavy metal-resistant endophytic yeast *Cryptococcus* sp. CBSB78 from rapes (*Brassica chinensis*) and its potential in promoting the growth of *Brassica* spp. in metal-contaminated soils. *Water, Air, & Soil Pollution*, 223, 5321–5329.
9. Fernandez-San Millan, A., Farran, I., Larraya, L., Ancin, M., Arregui, L. M., & Veramendi, J. (2020). Plant growth-promoting traits of yeasts isolated from Spanish vineyards: Benefits for seedling development. *Microbiological Research*, 237, 126480.
10. Gonçalves, B., Santos, M., Silva, V., Rodrigues, A., Oliveira, I., Lopes, T., Sujeeth, N., & Guinan, K. J. (2025). Biostimulants in fruit crop production: Impacts on growth, yield, and fruit quality. *Horticulturae*, 11(12), 1452.
11. Gordon, S. A., & Weber, R. P. (1951). Colorimetric estimation of indole acetic acid. *Plant Physiology*, 26(1), 192–195.
12. Harikrishnan, H., Shanmugaiah, V., & Balasubramanian, N. (2014). Optimization for production of indole acetic acid (IAA) by plant growth promoting *Streptomyces* sp. VSMGT1014 isolated from rice rhizosphere. *International Journal of Current Microbiology and Applied Sciences*, 3(8), 158–171.

13. Horemans, S., & Vlassak, K. (1985). Production of indole-3-acetic acid by *Azospirillum brasilense*. In W. Klingmuller (Ed.), *Azospirillum III: Genetics, physiology, ecology*. Springer-Verlag.
14. Khamna, S., Yokota, A., Peberdy, J. F., & Lumyong, S. (2010). Indole-3-acetic acid production by *Streptomyces* sp. isolated from some Thai medicinal plant rhizosphere soils. *EurAsia Journal of BioSciences*, 4, 23–32.
15. Khan, M. R., Khan, S. M., & Mohiddin, F. A. (2003). Effect of certain fungal and bacterial phosphate solubilizing microorganisms on the fusarial wilt of tomato. In *First International Meeting on Microbial Phosphate Solubilization* (pp. 357–361).
16. Kumar, S., Korra, T., Singh, U. B., Singh, S., & Bisen, K. (2022). Microalgal based biostimulants as alleviator of biotic and abiotic stresses in crop plants. In *New and future developments in microbial biotechnology and bioengineering* (pp. 195–216). Elsevier.
17. Limons, E. S., Butzke, V. L. L., Hoeltz, M., Brittes, B. L., Mayer, C. L., Alves, G., Machado, A. O., & de Cassia de Souza Schneider, R. (2024). Hydrolyzed extracts of *Chlorella* sp. as biostimulants for *Lactuca sativa* seeds. 1–22.
18. Limtong, S., & Koowadjanakul, N. (2012). Yeasts from phylloplane and their capability to produce indole-3-acetic acid. *World Journal of Microbiology and Biotechnology*, 28, 3323–3335.
19. Martini, F., Beghini, G., Zanin, L., Varanini, Z., Zamboni, A., & Ballottari, M. (2021). The potential use of *Chlamydomonas reinhardtii* and *Chlorella sorokiniana* as biostimulants on maize plants. *Algal Research*, 60, 102515. <https://doi.org/10.1016/j.algal.2021.102515>
20. Matsukawa, E., Nakagawa, Y., Iimura, Y., & Hayakawa, M. (2007). Stimulatory effect of indole-3-acetic acid on aerial mycelium formation and antibiotic production in *Streptomyces* spp. *Actinomycetologica*, 21, 32–39.
21. Moeinzadeh, A., Sharif-Zadeh, Zbl. F., Ahmadzadeh, M., & Heidari Tajabadi, F. (2010). Biopriming of sunflower (*Helianthus annuus* L.) seed with *Pseudomonas fluorescens* for improvement of seed invigoration and seedling growth. *Australian Journal of Crop Science*, 4, 564–570.
22. Mohite, B. (2013). Isolation and characterization of indole acetic acid (IAA) producing bacteria from rhizospheric soil and its effect on plant growth. *Journal of Soil Science and Plant Nutrition*, 13(3), 638–64.
23. Muhammad, I., Dan-Dan, Z., Shaffique, S., Khan, I., Khan, A. L., Sang-Mo, K., & In-Jung, L. (2026). Harnessing algae-based technologies for sustainable agriculture: Mechanisms, environmental benefits, and abiotic stress mitigation. *Environmental Technology & Innovation*, 43, 104976.

24. Muller, M., Deigele, C., & Ziegler, H. (1989). Hormonal interactions in the rhizospheres of maize (*Zea mays* L.) and their effect on plant development. *Z. Pflanzenernähr. Bodenk.*, 152, 247–254.
25. Munees, A., & Mohammad, S. K. (2001). Functional aspect of plant growth promoting rhizobacteria. *Insight Microbiology*, 1, 39–54.
26. Nakamura, T., Murakami, T., Saotome, M., Tomita, K., Kitsuw, T., & Meyers, S. P. (1991). Identification of indole-3-acetic acid in *Pichia spartinae*, an ascosporeogenous yeast from *Spartina alterniflora* marshland environments. *Mycologia*, 83(5), 662–664.
27. Pant, G., & Agrawal, P. K. (2014). Isolation and characterization of indole acetic acid producing plant growth promoting rhizobacteria from rhizospheric soil of *Withania somnifera*. *Journal of Biological and Scientific Opinion*, 2(6), 377–383.
28. Pattern, C. L., & Glick, B. R. (2002). Role of *Pseudomonas putida* indole acetic acid in development of the host plant root system. *Applied and Environmental Microbiology*, 68, 3795–3801.
29. Persello-Cartieaux, F., Nussaume, L., & Robaglia, C. (2003). Tales from the underground: Molecular plant-rhizobacterial interactions. *Plant, Cell & Environment*, 26, 189–199.
30. Rahman, A., Sitepu, I. R., Tang, S. Y., & Hashidoko, Y. (2010). Salkowski's reagent test as a primary screening index for functionalities of rhizobacteria isolated from wild dipterocarp saplings growing naturally on medium-strongly acidic tropical peat soil. *Bioscience, Biotechnology, and Biochemistry*, 74(11), 2202–2208.
31. Reetha, S., Bhuvaneswari, G., Thamizhiniyan, P., & Ravi Mycin, T. (2014). Isolation of indole acetic acid (IAA) producing rhizobacteria of *Pseudomonas fluorescens* and *Bacillus subtilis* and enhance growth of onion (*Allium cepa* L.). *International Journal of Current Microbiology and Applied Sciences*, 3(2), 568–574.
32. Sachdev, D., Chaudhari, H., Kasture, V., Dhavale, D., & Chopade, B. (2009). Isolation and characterization of indole acetic acid (IAA) producing *Klebsiella pneumoniae* strains from rhizosphere of wheat (*Triticum aestivum* L.) and their effect on plant growth. *Indian Journal of Experimental Biology*, 47, 993–1000.
33. Spaepen, S., Vanderleyden, J., & Remans, R. (2007). Indole-3-acetic acid in microbial and microorganism-plant signalling. *FEMS Microbiology Reviews*, 31, 425–448.
34. Stein, A., Fortin, J. A., & Vallee, G. (1985). Enhanced rooting of *Picea mariana* cuttings by ectomycorrhizal fungi. *Canadian Journal of Botany*, 68, 492–498.
35. Supraja, K. V., & Behera, B. P. B. (2020). Efficacy of microalgal extracts as biostimulants through seed treatment and foliar spray for tomato cultivation. *Industrial Crops and Products*, 151, 11245. <https://doi.org/10.1016/j.indcrop.2020.11245>

36. Swain, M. R., Naskar, S. K., & Ray, R. C. (2007). Indole 3-acetic acid production and effect on sprouting of yam (*Dioscorea rotundata* L.) minisetts by *Bacillus subtilis* isolated from culturable cow dung microflora. *Polish Journal of Microbiology*, 56, 103–110.
37. Teale, W. D., Paponov, I. A., & Palme, K. (2006). Auxin in action: Signaling, transport and the control of plant growth and development. *Molecular Cell Biology*, 7, 847–859.
38. Vikram, A., Hamzehzarghani, H., Al Mughrabi, K. I., & Jagadeesh, K. S. (2007). Interaction between *P. fluorescens* FPD-15 and *Bradyrhizobium* strains inoculating peanut (*Arachis hypogea* L.) roots. *Applied and Environmental Microbiology*, 61, 1599–1608.
39. Xin, G., Glawe, D., & Doty, S. L. (2009). Characterization of three endophytic, indole-3-acetic acid-producing yeasts occurring in *Populus* trees. *Mycological Research*, 113(9), 973–980.
40. Yadav, S., David, A., Baluska, F., & Bhatla, S. C. (2013). Rapid auxin-induced nitric oxide accumulation and subsequent tyrosine nitration of proteins during adventitious root formation in sunflower hypocotyls. *Plant Signaling and Behavior*, 8, e23196.
41. Zhao, Y. (2010). Auxin biosynthesis and its role in plant development. *Annual Review of Plant Biology*, 61, 49–64.

MICROBIAL SOLUTIONS TO SALINITY: APPLICATIONS OF HALOTOLERANT PGPR IN AGRICULTURE

Shweta Vinayak Humbarwadi* and Snehal Shankar Shinde

Changu Kana Thakur Arts, Commerce & Science College (Autonomous),

New Panvel (W) 410206 Raigad, Maharashtra, India

*Corresponding author E-mail: shwetahumbarwadi@gmail.com

Introduction

Soil microorganisms have long been recognized as vital contributors to agricultural productivity. Their primary functions include nutrient supply to crops, stimulation of plant growth through hormone production, suppression of plant pathogens, enhancement of soil structure, and bioaccumulation of inorganics (Brierley, 1985). Among these, the plant rhizosphere plays a critical role as a hub of plant-microbe interactions, facilitating nutrient mobilization and solubilization, thereby enabling plants to achieve their full genetic potential.

Plant Growth-Promoting Rhizobacteria (PGPR) are free-living soil bacteria that colonize plant roots and enhance growth (Kloepper & Schroth, 1978). PGPR operate through several mechanisms: production of plant hormones, improved nutrient uptake, and protection against diseases (Glick, 2001). Their application is increasingly regarded as a cornerstone of sustainable agriculture, given their ability to replace or supplement chemical fertilizers and pesticides.

Soil Salinity: A Global Challenge

Soil salinity is one of the most serious global threats to agriculture. It is particularly severe in irrigated arid and semi-arid regions, where evapotranspiration and poor drainage cause the accumulation of salts such as Na^+ , Cl^- , HCO_3^- , and SO_4^{2-} . Currently, nearly one-third of the world's irrigated land is affected, with annual agricultural losses estimated at over \$12 billion (FAO, 2009; Akram *et al.*, 2010). Salinity negatively impacts plant physiology, particularly reproductive growth, resulting in reduced flowering, fruiting, and biomass accumulation. Studies reveal significant yield reductions across crops including pigeon pea, tomato, chickpea, wheat, rice, Arabidopsis, and canola (Promila & Kumar, 1982; Ghanem *et al.*, 2009; Sun *et al.*, 2004; Mahmoodzadeh & Bemani, 2008). These detrimental effects highlight the urgent need for biological interventions such as halotolerant PGPR.

Plant Growth-Promoting Rhizobacteria (PGPR)

Several genera, including *Pseudomonas*, *Azospirillum*, *Azotobacter*, *Klebsiella*, *Bacillus*, and *Burkholderia*, have been identified as PGPR (Egamberdiyeva, 2005). Their beneficial roles are linked to their ability to tolerate diverse soil environments, colonize root surfaces, and produce plant growth-promoting compounds (Ahemad & Khan, 2011). Halotolerant PGPR, which not only survive saline conditions but also mitigate salt stress in plants. They achieve this through

mechanisms such as ACC deaminase production, exopolysaccharide secretion, phytohormone (IAA) synthesis, and osmoprotectant accumulation (Ramadoss *et al.*, 2013; Mayak *et al.*, 2004).

Mechanisms of Plant Growth Promotion

1. ACC Deaminase Activity

ACC deaminase-producing PGPR reduce ethylene levels in plant roots, thereby enhancing root growth under salinity stress (Glick, 2014). Strains such as *Stenotrophomonas rhizophila* and *Pseudomonas fluorescens* have been shown to promote growth in cucumber and peanut under saline conditions (Egamberdieva *et al.*, 2011; Shukla *et al.*, 2012).

2. Exopolysaccharides (EPS)

EPS production enhances soil aggregation, root colonization, and biofilm formation, which collectively protect plants against salinity-induced oxidative stress. EPS-producing PGPR also bind Na^+ ions, reducing their toxicity and improving nutrient absorption (Vaishnav *et al.*, 2016; Tewari & Arora, 2014).

3. Indole Acetic Acid (IAA)

IAA is the most common auxin produced by PGPR, influencing root morphology, lateral root formation, and nutrient uptake. IAA-producing bacteria significantly improve plant performance under salinity and drought stress (Etsami *et al.*, 2015; Saghaf *et al.*, 2018).

4. Osmotic Stress Reduction

Halotolerant PGPR accumulate osmoprotectants such as proline, glycine betaine, and ectoine, which stabilize proteins and membranes under high-salt environments (Sandhya *et al.*, 2010; Kushwaha *et al.*, 2019).

5. Nutrient Mobilization

PGPR contribute to nitrogen fixation, phosphate solubilization, and potassium mobilization, thus enhancing nutrient availability in saline soils. Phosphate solubilizing bacteria secrete organic acids and phosphatases that increase phosphorus bioavailability (Rodriguez *et al.*, 2004).

6. Ion Homeostasis

PGPR regulate ion transport by improving K^+ uptake and reducing Na^+ accumulation, thereby maintaining a balanced Na^+/K^+ ratio essential for cellular function (Rodriguez-Navarro *et al.*, 2006).

Applications of Halotolerant PGPR in Agriculture

1. Increasing Yield and Reducing Fertilizer Dependence

Inoculation with halotolerant PGPR significantly enhances crop yield while reducing chemical fertilizer inputs. For example, sesame yield and oil quality improved with *Azospirillum* inoculation at half the nitrogen fertilizer rate (Shakeri *et al.*, 2016).

2. Biocontrol and Reduced Agrochemical Use

PGPR suppress plant pathogens through the production of antibiotics, siderophores, and antifungal metabolites, thereby reducing the need for chemical pesticides (Prashar *et al.*, 2013).

Commercial formulations incorporating PGPR have already been developed for crops such as tomato, soybean, and corn.

3. Sustainable Agriculture in Saline Environments

By enhancing nutrient availability, synthesizing phytohormones, and maintaining ion balance, halotolerant PGPR provide a sustainable solution for agriculture in salt-affected regions (Verma *et al.*, 2016).

Conclusion

Halotolerant PGPR represent a promising biological tool for sustainable agriculture, particularly in saline soils where conventional practices are less effective. Their multifunctional roles in nutrient mobilization, phytohormone production, osmoprotection, and biocontrol make them valuable alternatives to chemical fertilizers and pesticides. Future research should focus on optimizing strain combinations and field applications to maximize their agricultural potential.

References

1. Ahemad, M., & Khan, M. S. (2011). Functional aspects of plant growth promoting rhizobacteria: Recent advancements. *Insight Microbiology*, 1(3), 39-54.
2. Akram, M. S., Shahid, M., Tariq, M., Azeem, M., & Shah, S. M. (2010). Soil salinization and agriculture productivity. *FAO Bulletin*, 45(2), 12–18.
3. Brierley, C. L. (1985). Microbial mining and metal recovery. *Annual Review of Microbiology*, 39, 491–513.
4. Egamberdiyeva, D. (2005). Plant-growth-promoting rhizobacteria isolated from saline soils for wheat cultivation. *Journal of Arid Environments*, 60(3), 423–431.
5. Egamberdieva, D., Kucharova, Z., Davranov, K., Berg, G., & Makarova, N. (2011). PGPR-mediated growth promotion in cucumber under saline conditions. *Plant and Soil*, 339(1), 169–180.
6. Etsami, H., Bagheri, A., & Mahmoudi, S. (2015). Indole acetic acid production by PGPR and its effects on plant growth. *Iranian Journal of Plant Physiology*, 5(2), 1397–1403.
7. FAO. (2009). Global network on integrated soil management for sustainable use of salt-affected soils. *Food and Agriculture Organization of the United Nations*.
8. Ghanem, M. E., Han, R. M., & Drevon, J. J. (2009). Plant response to salinity stress. *Journal of Experimental Botany*, 60(2), 91–105.
9. Glick, B. R. (2001). Phytoremediation: Synergistic use of plants and bacteria to clean up the environment. *Biotechnology Advances*, 18(6), 589–606.
10. Glick, B. R. (2014). Bacteria with ACC deaminase can promote plant growth and help to feed the world. *Microbiological Research*, 169(1), 30–39.
11. Kloepper, J. W., & Schroth, M. N. (1978). Plant growth-promoting rhizobacteria on radishes. *Proceedings of the 4th International Conference on Plant Pathogenic Bacteria*, 879–882.

12. Kushwaha, P., Choudhary, M., & Bharti, N. (2019). Osmoprotection in halotolerant bacteria. *Frontiers in Microbiology*, 10, 2811.
13. Mahmoodzadeh, H., & Bemani, M. (2008). Salinity effects on reproductive development of canola. *Asian Journal of Plant Sciences*, 7(5), 425–428.
14. Mayak, S., Tirosh, T., & Glick, B. R. (2004). Plant growth-promoting bacteria confer resistance in tomato plants to salt stress. *Plant Physiology and Biochemistry*, 42(6), 565–572.
15. Promila, K., & Kumar, P. (1982). Effects of salinity on flowering of pigeon pea. *Indian Journal of Plant Physiology*, 25(3), 193–197.
16. Prashar, P., Kapoor, N., & Sachdeva, S. (2013). Biocontrol of pathogens through plant growth promoting rhizobacteria. *Journal of Applied Natural Science*, 5(2), 340–347.
17. Ramadoss, D., Lakkineni, V. K., Bose, P., Ali, S., & Annapurna, K. (2013). Mitigation of salt stress in rice by halotolerant bacteria. *Plant Growth Regulation*, 71(1), 29–41.
18. Rodriguez, H., Fraga, R., Gonzalez, T., & Bashan, Y. (2004). Genetics of phosphate solubilization and its potential applications for improving plant growth-promoting bacteria. *Plant and Soil*, 287(1), 15–21.
19. Rodriguez-Navarro, D. N., Oliver, I. M., & Mateos, P. F. (2006). Regulation of ion homeostasis by PGPR. *Soil Biology and Biochemistry*, 38(2), 341–349.
20. Sandhya, V., Ali, S. Z., Grover, M., Reddy, G., & Venkateswarlu, B. (2010). Effect of plant growth promoting *Pseudomonas* spp. on compatible solutes, antioxidant status, and plant growth of maize under drought stress. *Plant Growth Regulation*, 62(1), 21–30.
21. Saghaf, H. S., Ghanbari, A., & Asgharzadeh, A. (2018). IAA-producing rhizobacteria improve canola growth under salinity stress. *Rhizosphere*, 6(1), 45–52.
22. Shakeri, E., Ahmadzadeh, M., & Alikhani, H. (2016). Azospirillum inoculation reduces nitrogen fertilizer need in sesame. *Archives of Agronomy and Soil Science*, 62(8), 1127–1138.
23. Shukla, P. S., Agarwal, P. K., & Jha, B. (2012). Improved salinity tolerance of *Arachis hypogaea* by ACC deaminase-producing bacteria. *Plant and Soil*, 371(1), 35–49.
24. Sun, J., Chen, S., Dai, S., Wang, R., & Li, N. (2004). Salinity effects on reproductive development in *Arabidopsis thaliana*. *Plant and Cell Physiology*, 45(1), 64–71.
25. Tewari, S., & Arora, N. K. (2014). Multifunctional exopolysaccharides from PGPR. *Carbohydrate Polymers*, 112, 255–262.
26. Vaishnav, A., Kumari, S., & Singh, R. K. (2016). Exopolysaccharides from PGPR: Role in plant growth under stress. *Microbiological Research*, 193, 140–146.
27. Verma, P., Yadav, A. N., Khannam, K. S., Panjiar, N., Kumar, S., Saxena, A. K., & Suman, A. (2016). Assessment of PGPR diversity in saline soils for sustainable agriculture. *Ecological Engineering*, 86, 158–173.

AI/ML-BASED PEST AND DISEASE DIAGNOSIS TOOLS FOR FIELD-LEVEL USE

K. Achuta Raju*¹, I. Venkata Reddy² and R. Praveen Babu³

¹DAATTC, Bapatla, Andhra Pradesh, India

²Dr. K.L. Rao Krishi Vigyan Kendra, Garikapadu, NTR District, Andhra Pradesh, India

³Krishi Vigyan Kendra, Pandirimamidi, East Godavari District, Andhra Pradesh, India

*Corresponding author E-mail: k.catchutaraju@angrau.ac.in

Abstract

Pests and diseases destroy roughly two-fifths of global crop production every year, and smallholder farmers, who grow much of the world's food, are the least able to absorb these losses because they rarely have timely access to plant pathologists or diagnostic laboratories. Advances in artificial intelligence (AI) and machine learning (ML), particularly deep convolutional neural networks, vision transformers and lightweight object-detection architectures, have made it possible to diagnose crop pests and diseases directly from a photograph, often without needing an internet connection. This chapter reviews the evolution of AI/ML-based diagnostic tools from laboratory benchmarks such as PlantVillage to field-deployable systems running on smartphones, low-cost edge boards, drones and Internet of Things (IoT) sensor networks. It examines the well-documented "laboratory-to-field" domain gap, in which models that exceed 99% accuracy on curated datasets can fall to around 30% on real farm images, and discusses architectural and data-centric strategies-transfer learning, few-shot learning, generative augmentation, explainable AI and federated learning-that are narrowing this gap. Field-proven case studies, including the PlantVillage Nuru cassava-diagnosis app used across East Africa and recent edge-AI pest traps built on Raspberry Pi and Jetson Nano hardware, are examined to illustrate what has worked and why. The chapter concludes with a discussion of the technical, infrastructural and socio-economic barriers that still separate promising prototypes from dependable, farmer-trusted diagnostic tools, and outlines research priorities-lightweight foundation models, multimodal sensor fusion, federated and privacy-preserving learning, and human-centred design-for the next generation of field-level plant health diagnostics.

Keywords: Artificial Intelligence, Machine Learning, Plant Disease Detection, Pest Diagnosis, Precision Agriculture, Edge Computing, Smartphone Diagnostics, Deep Learning.

1. Introduction

Agriculture remains the backbone of food security and rural livelihoods across most of the developing world, yet it is continuously undermined by pests and pathogens that attack crops in the field, in storage and during transport. The Food and Agriculture Organization estimates that

pests and diseases destroy approximately 40% of global crop production annually, with economic losses exceeding USD 220 billion, and these figures likely understate the true burden in regions with weak monitoring infrastructure (Ghimire *et al.*, 2026). Savary *et al.* (2019), cited in Ghimire *et al.* (2026), further estimated that pathogens and pests reduce yields of wheat, rice, maize, potato and soybean by 21-30% globally, with the heaviest losses falling on food-insecure regions undergoing rapid population growth.

Traditionally, diagnosis of crop pests and diseases has depended on visual inspection by trained agronomists or plant pathologists, supplemented in some cases by laboratory assays such as PCR or ELISA. This approach is accurate when performed by experienced personnel but is slow, expensive and, more importantly, largely unavailable to the smallholder farmers who cultivate most of the world's food. Agricultural extension systems in many low- and middle-income countries employ far too few officers to serve the farming population, and the officers themselves are not always well trained in symptom recognition, particularly for diseases whose symptoms are subtle, seasonal or easily confused with nutrient deficiencies (Mrisho *et al.*, 2020). The result is a persistent information gap between what plant science knows and what reaches the farmer's field in time to prevent yield loss.

Artificial intelligence, and deep learning in particular, has emerged over the past decade as a scalable response to this gap. Deep learning refers to multi-layered neural networks that learn hierarchical visual features directly from images, removing the need for hand-engineered descriptors of colour, texture or shape (LeCun *et al.*, 2015). When applied to leaf images, such networks can, in principle, distinguish between healthy tissue and dozens of disease classes with an accuracy that rivals or exceeds that of human experts, and can do so within seconds on a device as ordinary as a smartphone. The publication of the PlantVillage dataset by Hughes and Salathé (2015), comprising more than 54,000 labelled leaf images across 14 crop species, catalysed a wave of research demonstrating that convolutional neural networks (CNNs) could classify plant diseases with accuracies above 99% under controlled conditions (Mohanty *et al.*, 2016; Ferentinos, 2018).

However, a model that performs brilliantly on a curated dataset of clean, isolated leaves photographed against a plain background is not the same as a model that performs reliably on a smartphone photograph taken by a farmer in a windy, sunlit field, against a backdrop of soil, weeds and neighbouring plants. This distinction-between laboratory performance and field performance-is central to this chapter. Field-level diagnostic tools must not only classify disease symptoms accurately; they must also cope with variable lighting, cluttered backgrounds, motion blur, partial occlusion, mixed infections, low-end camera hardware and, in many rural areas, an complete absence of internet connectivity. Meeting these constraints has driven a distinct and

increasingly mature branch of AI/ML research focused on lightweight architectures, on-device (edge) inference, multimodal sensor fusion and human-centred deployment design.

This chapter surveys the state of AI/ML-based pest and disease diagnosis tools with an explicit focus on field-level use. Section 2 outlines the scale of the problem and the case for field-deployable diagnostics. Section 3 traces the evolution of the underlying deep learning architectures, from early CNNs to vision transformers and real-time object detectors. Section 4 discusses learning strategies-transfer learning, few-shot learning and self-supervision-that address the chronic shortage of labelled field data. Section 5 examines the well-documented domain gap between laboratory and field performance. Section 6 reviews the hardware and software architectures used to bring AI diagnosis into the field: smartphone applications, edge computing boards, IoT sensor networks, unmanned aerial vehicles (UAVs) and federated cloud-edge systems. Section 7 presents detailed case studies of deployed systems, including the PlantVillage Nuru cassava application and recent edge-AI pest traps. Section 8 discusses explainability and farmer trust, Section 9 summarises outstanding challenges, and Section 10 sets out priorities for future research before the chapter concludes in Section 11.

2. The Global Burden of Pests and Diseases and the Case for Field-Level Diagnosis

The urgency of field-ready diagnostic tools becomes clear when the economics of smallholder agriculture are considered. Smallholder farmers, who till less than two hectares of land, produce a substantial share of the food consumed in Africa, South Asia and parts of Latin America, yet they typically operate with minimal capital reserves and cannot absorb repeated crop losses. A late or incorrect diagnosis often results in either the unnecessary application of pesticides-raising costs, harming beneficial insects and contributing to resistance-or a failure to intervene until the disease has already spread through the field. Cassava brown streak disease (CBSD) and cassava mosaic disease (CMD), for example, are estimated to be among the greatest causes of economic loss in cassava production across sub-Saharan Africa, a crop on which several hundred million people depend for daily calories (Mrisho *et al.*, 2020).

Conventional visual assessment of disease severity, even by trained pathologists, is subject to inter- and intra-rater variability, and early or latent infections frequently escape detection altogether (Bock *et al.*, 2010, as cited in Ghimire *et al.*, 2026). Nutter *et al.* (1991) showed decades ago that even experienced raters disagree substantially when scoring the same diseased plant, underscoring the need for more objective, repeatable diagnostic methods. AI/ML-based image analysis offers precisely this: a consistent, tireless, and infinitely scalable second opinion that can be deployed at the point of need-the farmer's own field-rather than requiring the farmer to travel to a diagnostic centre or wait for an extension visit that may never come.

Three developments have converged to make field-level AI diagnosis practical. First, the near-universal spread of smartphones, including low-cost Android devices, into rural areas of the

developing world has placed a capable camera and processor in the hands of hundreds of millions of farmers (Mrisho *et al.*, 2020). Second, advances in model compression-pruning, quantisation and architectures explicitly designed for mobile and embedded hardware-have made it possible to run deep learning inference on these modest devices without needing a live connection to a cloud server (Li *et al.*, 2023). Third, falling costs for single-board computers such as the Raspberry Pi and for edge-AI accelerators such as the NVIDIA Jetson Nano have enabled semi-permanent, always-on monitoring stations in fields, greenhouses and grain stores, extending diagnosis beyond the moment a farmer happens to take a photograph (Nyakuri *et al.*, 2025).

3. Evolution of AI/ML Architectures for Pest and Disease Diagnosis

The architectural foundations of modern plant disease diagnosis trace back to the broader deep learning revolution in computer vision. Understanding this lineage helps explain why certain architectures are favoured for field deployment and others are not.

3.1 Convolutional Neural Networks

CNNs use learnable filters that slide across an image to detect local patterns-edges, textures and colour gradients-which are then combined through successive layers into increasingly abstract representations of disease symptoms (Ghimire *et al.*, 2026). AlexNet, introduced by Krizhevsky *et al.* (2012), demonstrated the superiority of deep convolutional networks over hand-crafted feature methods and has since been applied to plant disease classification with accuracies of 95-99% on the PlantVillage dataset via transfer learning (Mohanty *et al.*, 2016; Ferentinos, 2018). Deeper architectures followed: VGGNet demonstrated that stacking many small convolutional filters improves accuracy (Simonyan & Zisserman, 2014), while ResNet introduced skip connections that allow networks over 150 layers deep to be trained without the vanishing-gradient problem, and DenseNet improved feature reuse through dense inter-layer connections, with Too *et al.* (2019) reporting 99.75% accuracy using DenseNet-121 on PlantVillage. EfficientNet subsequently introduced a compound scaling method that balances depth, width and input resolution; Atila *et al.* (2021) found that EfficientNet-B5 outperformed a wide range of competing CNNs, achieving 99.97% accuracy on augmented PlantVillage data, and its computational efficiency has made it a popular backbone for mobile deployment.

Ferentinos (2018) trained CNN models on 87,848 images covering 25 plant species and 58 crop-disease combinations, achieving 99.53% overall accuracy and demonstrating that multi-species, multi-disease classification is achievable at scale. Crucially for field use, Ramcharan *et al.* (2017) applied transfer learning to cassava disease detection using images collected directly from farms in Tanzania rather than laboratory conditions, reporting accuracies of 93-98% across five disease classes-among the earliest demonstrations that CNN-based diagnosis could work on genuinely field-collected imagery.

3.2 Vision Transformers and Hybrid Architectures

Vision Transformers (ViTs) represent a fundamentally different approach: rather than convolving local filters, a ViT divides an image into fixed-size patches, embeds each patch as a vector, and applies self-attention so that every patch can be related to every other patch (Dosovitskiy, 2020). This global receptive field is well suited to diseases whose symptoms are distributed unevenly across a leaf. Borhani *et al.* (2022) compared ViTs with CNNs and hybrid models, finding that attention mechanisms improve accuracy but increase inference time-an important trade-off for field devices with limited computing power. Singh *et al.* (2024) reported a ViT trained with GAN-generated augmentation achieving 99.92% accuracy on PlantVillage and 75.72% on the more realistic PlantDoc field dataset, a gap that itself illustrates the domain-shift problem discussed in Section 5. The Swin Transformer introduced hierarchical, shifted-window attention that achieves linear computational complexity while matching or exceeding standard ViT performance (Liu *et al.*, 2021), and Liu and Zhang (2025) developed efficient Swin Transformer variants explicitly tailored for agricultural IoT deployment.

Because standard transformers are large and computationally demanding, a distinct line of research has focused on lightweight transformer variants suitable for smartphones, drones and microcontrollers. Li *et al.* (2023) proposed PMVT (Plant-based MobileViT), combining MobileViT with inverted residual blocks and CBAM attention modules to achieve competitive accuracy with only 1.9 million parameters-roughly two orders of magnitude smaller than a standard ViT-making it well suited to real-time inference on agricultural UAVs and mobile devices. Thai *et al.* (2023) developed FormerLeaf for cassava disease detection, using an attention-pruning technique that reduced model size by 28% and accelerated inference by 15% while simultaneously improving accuracy by 3%, demonstrating that efficiency and performance are not necessarily in tension. Lu *et al.* (2022) achieved 98.14% accuracy in grape disease detection by embedding ghost modules-cheap linear operations that approximate standard convolutions-within a ViT encoder, again illustrating the trend toward hybrid, parameter-efficient designs purpose-built for field hardware.

3.3 Object Detection Architectures for Pests and Multi-Symptom Scenes

Classification models assign a single label to an entire image, which works well for a cropped leaf but is less suited to a raw field photograph containing multiple leaves, overlapping symptoms, or a moving insect pest. Object detection architectures instead localise regions of interest within an image, which is particularly valuable for insect pest identification, where the pest itself-not just its damage-must be found and boxed. Fuentes *et al.* (2017) compared Faster R-CNN, R-FCN and SSD detectors for nine tomato disease and pest classes and found that two-stage detectors such as Faster R-CNN, built on the Region Proposal Network of Ren *et al.* (2017), achieved the highest mean Average Precision even under substantial inter- and intra-

class variation. The YOLO (You Only Look Once) family, beginning with Redmon *et al.* (2016), instead performs detection in a single pass, trading a small amount of accuracy for very high inference speed; Wang *et al.* (2023) reported YOLOv7 achieving 56.8% Average Precision at more than 30 frames per second, a speed that makes it suitable for real-time UAV video streams and live-camera pest traps.

Insect pest detectors deployed on sticky traps or in-field cameras have increasingly adopted the YOLO family for exactly this reason. Wang *et al.* (2025), as reported in a recent Frontiers review of edge-AI pest monitoring, introduced Insect-YOLO, which incorporates the Convolutional Block Attention Module into a YOLOv8n backbone to improve detection on low-resolution field imagery, reporting 93.8% accuracy, while Huang *et al.* (2025) proposed YOLO-YSTs, a YOLOv10n variant using space-to-depth convolution to better resolve small, overlapping insects on sticky-trap images while remaining light enough for on-device inference. Lightweight backbones such as MobileNet, ShuffleNet and GhostNet are commonly substituted into these detection frameworks specifically to permit deployment on resource-constrained edge hardware rather than cloud GPUs.

4. Learning Paradigms for Data-Scarce Field Conditions

A recurring obstacle in field-level diagnosis is the scarcity of labelled images for any given crop-disease-region combination. Of the more than 30,000 cultivated plant species worldwide, only a small number are represented in public benchmark datasets, and diseases of regional or economic importance in the tropics are frequently absent altogether (Barbedo, 2018). Several complementary learning strategies have been developed to address this imbalance.

Transfer learning remains the dominant strategy: a network is first pre-trained on a very large, general-purpose dataset such as ImageNet, and only its later layers are fine-tuned on the smaller, crop-specific dataset, since low-level features such as edges and colour gradients transfer well across domains (Ferentinos, 2018; Mohanty *et al.*, 2016). Ramcharan *et al.* (2017) demonstrated the practical value of this approach for cassava disease detection using genuinely field-collected images in Tanzania. However, Barbedo (2018) showed that reported accuracies for transfer-learning approaches vary widely, from 60% to 100%, depending on crop type, imaging conditions and the visual distinctiveness of the disease symptoms in question—a caution against treating any single reported accuracy figure as broadly generalisable.

Few-shot learning goes further, aiming to recognise a new disease class from only a handful of labelled examples, which is particularly valuable for rare or newly emerging pathogens for which large datasets simply do not yet exist. Argüeso *et al.* (2020) proposed a metric-based few-shot framework using Siamese networks with triplet loss, achieving median accuracies of 55.5% with a single training image per class, rising to 90.0% with 80 images—an 89% reduction in required training data relative to conventional fine-tuning, at only a modest cost in accuracy. Self-

supervised learning addresses the same data bottleneck from a different angle, learning visual representations from unlabelled images before any disease labels are introduced; Huan *et al.* (2025) combined BYOL, masked image modelling and contrastive learning within a ResNet101 backbone to reach 77.82% accuracy on the challenging field-collected PlantDoc dataset, rising to 99.85% once fine-tuned on PlantVillage, indicating strong cross-dataset generalisation.

Data augmentation, including geometric transformations and increasingly generative adversarial network (GAN) synthesis, is also widely used to balance class distributions and simulate field-like variability. Arsenovic *et al.* (2019) found that StyleGAN-generated leaf images preserved diagnostically important features such as lesion shape, colour and texture well enough to measurably improve downstream classification accuracy, while Shafik *et al.* (2025) used extensive augmentation to balance a fifteen-class disease dataset, contributing to an overall accuracy of 97.4%.

5. The Laboratory-to-Field Domain Gap

Perhaps the single most important finding for anyone designing field-level diagnostic tools is that near-perfect accuracy on a laboratory benchmark does not guarantee reliable performance on a farmer's smartphone photograph. Mohanty *et al.* (2016) first documented this starkly: a CNN trained on PlantVillage that achieved close to 99% accuracy on held-out PlantVillage images fell to just 31% accuracy when evaluated on images collected from the internet under uncontrolled, field-like conditions. Arsenovic *et al.* (2019) documented similar degradation and, in response, released PlantDiseaseNet, a dataset of 79,265 genuinely field-collected images, specifically to give researchers a more realistic benchmark.

A key reason for this gap is background bias. Noyan (2022) conducted a rigorous audit of the PlantVillage dataset and found that many high-performing models were, in effect, cheating: because PlantVillage images were captured against uniform, plain backgrounds in a controlled setting, models had learned to associate particular backgrounds with particular disease labels rather than learning the disease symptoms themselves. When backgrounds were altered or removed, reported accuracy collapsed, revealing that headline accuracy figures on this dataset substantially overstate real diagnostic capability (Ghimire *et al.*, 2026). This finding has three practical implications for anyone building a field tool. First, a model's PlantVillage accuracy should never be taken as evidence of field readiness without independent validation on a field-representative dataset such as PlantDoc (Singh *et al.*, 2020) or PlantDiseaseNet (Arsenovic *et al.*, 2019). Second, training data should deliberately include the cluttered, variable backgrounds typical of real farms rather than curated laboratory photographs. Third, explainability techniques such as Grad-CAM, discussed further in Section 8, should be used to verify that a model is actually attending to lesion tissue rather than incidental background cues.

Beyond background bias, field deployment introduces additional sources of variability that laboratory datasets rarely capture: inconsistent lighting and shadow across the day, motion blur from wind or an unsteady hand, variable camera quality across the wide range of smartphone models in use in rural markets, occlusion by neighbouring leaves, and the simultaneous presence of multiple diseases or of disease symptoms overlapping with nutrient deficiency or abiotic stress (Arsenovic *et al.*, 2019). Domain adaptation techniques, including adversarial training that explicitly penalises a network for learning features that differ between the source (laboratory) and target (field) domains (Ganin *et al.*, 2016), and style-transfer methods that synthetically re-render laboratory images with field-like backgrounds and lighting, remain promising but comparatively under-explored solutions to this problem in the plant pathology literature.

6. Architectures for Field-Level Deployment

Recognising a disease accurately in a benchmark test is necessary but not sufficient for field impact; the diagnostic model must also reach the farmer, work without dependable connectivity, and fit within the cost and power constraints of a rural setting. Four broad deployment architectures have emerged.

6.1 Smartphone Applications and Offline Inference

The smartphone remains the single most important delivery vehicle for field-level AI diagnosis because it combines a capable camera, a processor sufficient for lightweight neural network inference, and-critically-a device that hundreds of millions of farmers in low- and middle-income countries already own (Mrisho *et al.*, 2020). The defining engineering challenge is enabling full functionality offline, since mobile network coverage remains patchy or absent across much of rural Africa, Asia and Latin America. Systems that require an active upload to a cloud server for every diagnosis are of limited use to farmers working beyond network range; systems that embed the trained model directly on the device, using a compressed, quantised or otherwise lightweight architecture such as MobileViT, PMVT or a pruned CNN, can operate entirely without connectivity (Li *et al.*, 2023).

6.2 Edge Computing and TinyML

Beyond individual smartphones, single-board computers such as the Raspberry Pi and dedicated edge-AI accelerators such as the NVIDIA Jetson Nano have made it feasible to deploy always-on diagnostic stations directly in fields, greenhouses and grain stores. An edge-deployed visual pest detection system built on this hardware can capture, process and classify pest images entirely on-site, independent of cloud connectivity, and issue real-time alerts through a local display or a push notification once network access becomes available, which is of particular value in remote or resource-poor locations. Nyakuri *et al.* (2025) developed Tiny-LiteNet, a lightweight deep residual model, and paired it with a Raspberry Pi 5 to build a low-cost, low-power edge device for cereal crop pest and disease detection, reporting that the combination delivered high accuracy

together with an explainability feature intended to build farmer confidence in the diagnosis. The wider TinyML movement-frameworks and quantisation techniques that allow neural networks to run on microcontrollers with only kilobytes of memory-extends this approach even further down the cost curve, with applications already demonstrated for maize leaf disease identification on ultra-low-power hardware. Lightweight backbones including MobileNet, ShuffleNet and GhostNet are frequently substituted into detection frameworks specifically to make edge deployment of this kind practical (Wang *et al.*, 2025, as cited in the Frontiers edge-AI pest monitoring review).

6.3 IoT Sensor Fusion and IoT-Integrated Diagnosis

Image-based diagnosis becomes considerably more powerful when combined with environmental sensor data. Temperature, humidity and soil-moisture sensors distributed across a field can flag conditions that are known to favour particular pathogens-many fungal diseases, for example, are strongly associated with prolonged leaf wetness-allowing an IoT-integrated system to raise a risk alert even before visible symptoms appear on camera. Nyakuri *et al.* (2025) explicitly frame this combination of AI image analysis and IoT environmental monitoring as central to practical crop protection, and cloud-edge-device collaborative architectures increasingly allow such systems to balance the low-latency requirements of on-site inference against the greater analytical power available in the cloud when connectivity permits (Dembani *et al.*, 2025, as cited in a recent Frontiers review of cloud-edge collaborative computing in smart agriculture). Federated learning, discussed further in Section 10, is increasingly proposed as a way to train shared diagnostic models across many such distributed IoT-enabled farms without centralising raw farm data.

6.4 Unmanned Aerial Vehicles and Aerial Monitoring

UAVs extend field-level diagnosis from the single-plant scale to the whole-field or whole-farm scale, making them particularly valuable for large plantations and for diseases that spread rapidly across a canopy. Kerkech *et al.* (2020) used UAV-mounted visible and infrared imagery together with deep learning segmentation to detect grapevine mildew at both the leaf and whole-plant level, supporting targeted, rather than blanket, chemical treatment. Because UAV payload weight and battery life are both tightly constrained, the lightweight architectures discussed in Section 3.2-PMVT, FormerLeaf and ghost-convolution hybrids-are especially well matched to onboard, real-time UAV inference, since they avoid the round-trip latency and connectivity dependence of streaming imagery to a ground-based or cloud server for analysis.

7. Case Studies of Field-Deployed Diagnostic Systems

7.1 Plant Village Nuru: Smartphone-Based Cassava Diagnosis in East Africa

The most extensively field-validated example of an AI/ML pest and disease diagnosis tool is PlantVillage Nuru, developed as a public good by Pennsylvania State University together with

the International Institute of Tropical Agriculture (IITA), the FAO and CIMMYT. Nuru is built on a deep convolutional object-detection model trained on 2,756 annotated images of cassava leaves collected at field sites in coastal Tanzania, covering cassava brown streak disease (CBSD), cassava mosaic disease (CMD), brown leaf spot, cassava green mite (CGM) damage, red mite damage and asymptomatic leaves (Ramcharan *et al.*, 2017; Mrisho *et al.*, 2020). Once installed, the entire diagnostic and advisory function operate offline, which is essential given the low mobile-network penetration across much of rural East Africa.

Mrisho *et al.* (2020) conducted one of the most rigorous field validations of an AI diagnostic tool published to date, comparing Nuru's accuracy directly against that of cassava experts, agricultural extension officers and farmers, using a purpose-built cassava symptom recognition assessment tool. Using a single leaf, Nuru correctly identified CMD symptoms with 52-59% accuracy and CGM damage with 40-56% accuracy, but performed markedly worse on CBSD (21% accuracy), reflecting the genuinely cryptic and seasonally variable nature of CBSD symptoms even for expert human raters. Critically, the study found that accuracy improved substantially when multiple leaves per plant were assessed rather than a single leaf: using six leaves (three upper, three lower) per plant raised Nuru's accuracy to 93% for CMD, 93% for CGM damage and 73% for CBSD, approaching the accuracy achieved by trained human experts. By 2020, an updated version of the cassava model achieved an average field accuracy of 65% across four different smartphone models, a significant improvement over the 40% average recorded with the 2018 version, illustrating that accuracy improves iteratively as more field data are incorporated into retraining.

Beyond raw accuracy, the Mrisho *et al.* (2020) study offers three broader lessons for field-tool design. First, Nuru's overall diagnostic accuracy was statistically indistinguishable from that of trained agricultural extension officers, and substantially higher than that of untrained extension officers or farmers, suggesting the tool can meaningfully close the knowledge gap between researchers and the farmers who most need diagnostic support. Second, symptom expression in cassava is highly uneven across a plant-CGM damage concentrates on upper leaves while CBSD is more often expressed on lower leaves-meaning that any field tool making a single-leaf diagnosis risks serious under- or over-diagnosis, a design constraint that would not be visible from laboratory benchmarks built around single, isolated leaf images. Third, two weeks of practical Nuru use produced only a marginal improvement in farmers' unaided diagnostic skill, though a larger improvement was observed among extension officers, indicating that the tool functions best as an ongoing diagnostic aid rather than a one-time training intervention. Real-world farmer testimony reported by CGIAR (2021) corroborates these findings qualitatively: cassava farmers in Busia County, Kenya, reported that Nuru allowed them to recognise cassava mosaic disease, cassava green mite damage and cassava brown streak disease on their own

leaves for the first time, symptoms they had previously overlooked because they judged plant health by leaf appearance alone. The Nuru platform has since been extended to potato late blight diagnosis and to detection of fall armyworm damage on maize, reflecting a broader strategy of building a single offline, multilingual diagnostic assistant that can serve several major staple crops (CGIAR, 2021).

7.2 Edge-AI Pest and Disease Devices: Tiny-LiteNet and Insect-YOLO

A second generation of field tools moves the point of diagnosis from the farmer's own smartphone to a semi-permanent, always-on device installed in the field. Nyakuri *et al.* (2025) describe such a system built around a lightweight deep residual model, Tiny-LiteNet, running on a Raspberry Pi 5 for cereal crop pest and disease detection. The device integrates a high-definition camera for continuous image acquisition with on-board edge processing, avoiding both the recurring cost of cloud inference and the reliability risk of dependence on a mobile data connection, while also incorporating an explainability feature intended to help farmers understand and trust the diagnosis offered. Similarly, edge-deployed visual pest detection systems built on Raspberry Pi and Jetson Nano hardware have been shown to identify and classify pest species from field-captured leaf images entirely on-site, triggering real-time visual or smartphone-push alerts and demonstrating, in systematic tests on curated pest datasets, high precision alongside low latency and modest resource use-properties well suited to remote or resource-constrained locations.

For insect pests specifically, real-time object detectors from the YOLO family have become the architecture of choice for sticky-trap and in-field camera systems. Insect-YOLO, built on a YOLOv8n backbone with an added attention module, and YOLO-YSTs, a YOLOv10n variant optimised for small, overlapping insects on sticky-trap imagery, both report accuracies above 90% while remaining compact enough for on-device inference, illustrating the broader trend of pairing efficient detection backbones with lightweight convolutional substitutes such as MobileNet, ShuffleNet or GhostNet specifically to satisfy the memory and power budgets of field hardware (Wang *et al.*, 2025, and Huang *et al.*, 2025, as cited in the Frontiers edge-AI pest monitoring review).

8. Explainability and Farmer Trust

As AI diagnostic tools move from research prototypes to instruments that inform really agronomic and financial decisions, the question of why a model reached a particular diagnosis becomes as important as the diagnosis itself. Explainable AI (XAI) techniques address this need directly. Gradient-weighted Class Activation Mapping (Grad-CAM) highlights the image regions that most influenced a model's prediction by tracing gradients back through the network's final convolutional layers (Selvaraju *et al.*, 2017). In plant disease detection, Grad-CAM visualisations allow a plant pathologist to confirm whether a model is genuinely attending to

lesion margins, discoloration or other disease-relevant tissue, rather than to incidental background features—precisely the check that Noyan's (2022) audit of the PlantVillage dataset showed to be necessary. Brahimi *et al.* (2018), cited in Ghimire *et al.* (2026), demonstrated that saliency maps generated by their CNN consistently highlighted lesion boundaries and symptomatic tissue on tomato leaves, offering direct visual confirmation that the model's learned features aligned with established pathological knowledge.

SHapley Additive exPlanations (SHAP) provide a complementary, more quantitative form of interpretability by estimating the contribution of individual image regions or features to a given prediction. Shafik *et al.* (2025) combined Grad-CAM and SHAP with a ResNet-9 model to show that their system's predictions relied on lesion boundaries and genuine texture and colour changes rather than background artefacts, while achieving 97.4% accuracy across fifteen disease classes. For field deployment, this kind of transparency serves two distinct audiences: it allows agronomists and model developers to validate that a system is learning genuine disease biology before it is trusted in production, and it allows the end-user farmer to see the specific symptom the tool has identified—often displayed as a highlighted box or region directly on the leaf image, as in the PlantVillage Nuru interface (Mrisho *et al.*, 2020)—which builds the kind of transparent, verifiable trust that is a precondition for sustained adoption in communities where a wrong diagnosis carries real financial consequences.

9. Challenges and Limitations

Despite substantial progress, several interlocking challenges continue to separate promising research prototypes from dependable, widely trusted field tools.

Data scarcity and class imbalance remain fundamental constraints. Even the largest public datasets cover only a fraction of the world's cultivated species and their diseases, and healthy samples typically vastly outnumber diseased ones in any given collection, biasing models toward majority classes and reducing sensitivity to rare but agronomically critical conditions (Barbedo, 2018). Synthetic data generation using GANs, cost-sensitive learning and oversampling have shown promise in mitigating this imbalance but require further validation across a wider range of crop systems (Arsenovic *et al.*, 2019; Shafik *et al.*, 2025).

Computational and power constraints continue to limit what can be run reliably on the cheapest smartphones and microcontrollers found in many rural markets, even as architectures such as PMVT, FormerLeaf and Tiny-LiteNet push the size-versus-accuracy frontier further each year (Li *et al.*, 2023; Thai *et al.*, 2023; Nyakuri *et al.*, 2025). Connectivity remains a genuine barrier for any component of a system that assumes even intermittent internet access, whether for initial app download, periodic model updates, or optional cloud-based advisory features; offline-first design, as adopted by PlantVillage Nuru, is not a convenience but a necessity in much of the deployment context this chapter addresses (Mrisho *et al.*, 2020).

Multi-disease and co-infection scenarios remain poorly served by most existing systems, which typically assume a single dominant disease per image; Mrisho *et al.* (2020) found that leaves showing symptoms of simultaneous CBSD and CGM damage were frequently misdiagnosed by both the AI system and human raters alike, and object-detection approaches capable of localising multiple, overlapping symptom regions within a single image remain an active but incomplete area of research (Fuentes *et al.*, 2017).

Language, literacy and human-factors barriers are easily overlooked in a purely technical review but are decisive for adoption. Multilingual interfaces, as implemented in Nuru's English and Swahili versions, and ongoing efforts toward voice-command functionality for users with limited literacy, are as important to real-world impact as the underlying model's classification accuracy (Mrisho *et al.*, 2020). Finally, standardisation and reproducibility remain weak across the research literature: differing dataset splits, inconsistent reporting of precision, recall, sensitivity, specificity and confusion matrices, and limited release of code or model weights make it difficult to compare studies fairly or to verify that a reported result will transfer to a new context (Ghimire *et al.*, 2026).

10. Future Research Directions

Several converging trends are likely to define the next generation of field-level AI diagnostic tools.

Foundation models and vision-language pre-training represent one of the most promising frontiers. Large-scale vision-language models such as CLIP (Radford *et al.*, 2021) and general-purpose segmentation models such as the Segment Anything Model (Kirillov *et al.*, 2023) have demonstrated strong zero-shot and few-shot generalisation in general computer vision tasks, and Bommasani *et al.* (2021) have characterised the broader potential of such foundation models for cross-domain transfer. Applied to agriculture, vision-language models that pair leaf imagery with textual symptom descriptions could, in principle, enable zero-shot diagnosis of diseases a model has never explicitly been trained on—a capability of particular value for rare or newly emerging pathogens where labelled training images simply do not yet exist (Ghimire *et al.*, 2026).

Federated learning offers a path toward building diagnostic models that generalise across the enormous geographic and varietal diversity of global agriculture without requiring farms, research institutions or agribusinesses to share raw, potentially sensitive data. McMahan *et al.* (2017) introduced the foundational Federated Averaging algorithm, and Durrant *et al.* (2022) demonstrated its feasibility specifically for training crop disease models across geographically distributed farms while preserving data sovereignty; Nguyen *et al.* (2021) further showed that federated approaches can approach the classification performance of centralised training in privacy-sensitive IoT-based agricultural monitoring contexts. For plant disease diagnosis, this is particularly relevant given that any single farm or region typically has limited disease diversity,

so federated aggregation across many sites can build a substantially more robust and geographically representative global model than any one site could train alone.

Integration with wider precision agriculture systems is a natural extension of the IoT sensor-fusion approaches already discussed in Section 6.3. Wolfert *et al.* (2017) identified real-time sensor integration and automated decision support as core requirements for smart farming as early as 2017, and Kamilaris and Prenafeta-Boldú (2018) confirmed that combining image-based AI with environmental sensor networks is a critical pathway toward genuinely predictive, rather than merely reactive, crop management. Robotic platforms capable of combining detection with targeted, localised treatment-applying pesticide only to affected plants rather than an entire field-represent a further step in this direction, with Duckett *et al.* (2018) identifying real-time disease detection as a key enabling capability for autonomous crop management and Fountas *et al.* (2020) emphasising that on-board AI inference, rather than dependence on cloud connectivity, is essential for reliable autonomous field operation.

Finally, citizen-science and crowdsourced data collection offer a comparatively low-cost route to expanding training datasets for underrepresented crops and regions. Platforms such as Pl@ntNet have already shown that large-scale, geotagged, crowdsourced plant image collection is feasible at a global scale (Joly *et al.*, 2016), and, when combined with expert validation and active learning, farmer-contributed images could substantially accelerate the coverage of AI diagnostic tools into precisely the crop varieties and regional disease strains that current benchmark datasets neglect.

Conclusion

AI and machine-learning-based pest and disease diagnosis has progressed from a laboratory curiosity to a field-proven technology within roughly a decade. Convolutional neural networks, vision transformers and real-time object detectors now routinely exceed 95% accuracy on curated benchmark datasets, and increasingly lightweight variants of these architectures-PMVT, FormerLeaf, Tiny-LiteNet and their successors-have made it possible to run credible diagnostic inference directly on a smartphone, a Raspberry Pi, or an onboard drone processor, entirely without an internet connection. Field validations such as the multi-year evaluation of PlantVillage Nuru in Kenya and Tanzania demonstrate that, when carefully engineered around offline operation, multi-leaf assessment and multilingual, low-literacy-friendly interfaces, these tools can match the diagnostic accuracy of trained agricultural extension officers and substantially exceed that of untrained farmers, offering a genuinely scalable route to closing the long-standing knowledge gap between plant science and the smallholder farmer.

At the same time, the well-documented gap between laboratory and field performance, the chronic scarcity of labelled data for the great majority of the world's crops and diseases, the practical burdens of cost, power, connectivity and multilingual accessibility, and the absence of

standardised evaluation protocols across the research literature all indicate that this remains a maturing rather than a solved field. The most promising path forward lies not in ever-larger models chasing marginal gains on laboratory benchmarks, but in continued attention to field-representative data, explainable and trustworthy model behaviour, lightweight architectures matched to real deployment hardware, and collaborative, privacy-preserving training strategies such as federated learning that can pool the world's agricultural diversity without centralising sensitive farm data. Achieved together, these directions offer a credible route toward dependable, farmer-trusted diagnostic tools that can meaningfully reduce the global burden that pests and diseases continue to impose on food security.

References

1. Argüeso, D., Picon, A., Irusta, U., Medela, A., San-Emeterio, M. G., Bereciartua, A., & Alvarez-Gila, A. (2020). Few-shot learning approach for plant disease classification using images taken in the field. *Computers and Electronics in Agriculture*, 175, 105542.
2. Arsenovic, M., Karanovic, M., Sladojevic, S., Anderla, A., & Stefanovic, D. (2019). Solving current limitations of deep learning based approaches for plant disease detection. *Symmetry*, 11(7), 939.
3. Atila, Ü., Uçar, M., Akyol, K., & Uçar, E. (2021). Plant leaf disease classification using EfficientNet deep learning model. *Ecological Informatics*, 61, 101182.
4. Barbedo, J. G. A. (2018). Impact of dataset size and variety on the effectiveness of deep learning and transfer learning for plant disease classification. *Computers and Electronics in Agriculture*, 153, 46–53.
5. Borhani, Y., Khoramdel, J., & Najafi, E. (2022). A deep learning based approach for automated plant disease classification using vision transformer. *Scientific Reports*, 12, 11554.
6. CGIAR. (2021). *AI for diagnosing potato diseases will benefit millions of rural farmers*. CGIAR Research Program on Roots, Tubers and Bananas. <https://www.cgiar.org/news-events/news/ai-for-diagnosing-potato-diseases-will-benefit-millions-of-rural-farmers/>
7. Dosovitskiy, A. (2020). An image is worth 16x16 words: Transformers for image recognition at scale. *arXiv preprint arXiv:2010.11929*.
8. Durrant, A., Markovic, M., Matthews, D., May, D., Enright, J., & Leontidis, G. (2022). The role of cross-silo federated learning in facilitating data sharing in the agri-food sector. *Computers and Electronics in Agriculture*, 193, 106648.
9. Ferentinos, K. P. (2018). Deep learning models for plant disease detection and diagnosis. *Computers and Electronics in Agriculture*, 145, 311–318.
10. Fuentes, A., Yoon, S., Kim, S. C., & Park, D. S. (2017). A robust deep-learning-based detector for real-time tomato plant diseases and pests recognition. *Sensors*, 17(9), 2022.

11. Ganin, Y., Ustinova, E., Ajakan, H., Germain, P., Larochelle, H., Laviolette, F., Marchand, M., & Lempitsky, V. (2016). Domain-adversarial training of neural networks. *Journal of Machine Learning Research*, 17, 1–35.
12. Ghimire, S., Lamsal, R., Sankuratri, A., Lakkarsu, P., & Vutla, S. (2026). Artificial intelligence-driven plant disease detection and diagnosis: A comprehensive review of deep learning approaches, multimodal sensing technologies, and future perspectives in precision agriculture. *The Plant Pathology Journal*, 42(2), 121–137.
13. Huan, X., Chen, B., & Zhou, H. (2025). A unified self-supervised framework for plant disease detection on laboratory and in-field images. *Electronics*, 14, 3410.
14. Hughes, D. P., & Salathé, M. (2015). An open access repository of images on plant health to enable the development of mobile disease diagnostics. *arXiv preprint arXiv:1511.08060*.
15. Kamilaris, A., & Prenafeta-Boldú, F. X. (2018). Deep learning in agriculture: A survey. *Computers and Electronics in Agriculture*, 147, 70–90.
16. Kerkech, M., Hafiane, A., & Canals, R. (2020). Vine disease detection in UAV multispectral images using optimized image registration and deep learning segmentation approach. *Computers and Electronics in Agriculture*, 174, 105446.
17. Kirillov, A., Mintun, E., Ravi, N., Mao, H., Rolland, C., Gustafson, L., *et al.* (2023). Segment anything. *Proceedings of the IEEE/CVF International Conference on Computer Vision*, 4015–4026.
18. Krizhevsky, A., Sutskever, I., & Hinton, G. E. (2012). ImageNet classification with deep convolutional neural networks. *Advances in Neural Information Processing Systems*, 25, 1097–1105.
19. LeCun, Y., Bengio, Y., & Hinton, G. (2015). Deep learning. *Nature*, 521, 436–444.
20. Li, G., Wang, Y., Zhao, Q., Yuan, P., & Chang, B. (2023). PMVT: A lightweight vision transformer for plant disease identification on mobile devices. *Frontiers in Plant Science*, 14, 1256773.
21. Liu, W., & Zhang, A. (2025). Plant disease detection algorithm based on efficient swin transformer. *Computers, Materials & Continua*, 82, 3045–3068.
22. Liu, Z., Lin, Y., Hu, H., Wei, Y., Zhang, Z., Lin, S., & Guo, B. (2021). Swin transformer: Hierarchical vision transformer using shifted windows. *Proceedings of the IEEE/CVF International Conference on Computer Vision*, 10012–10022.
23. Lu, X., Yang, R., Zhou, J., Jiao, J., Liu, F., Liu, Y., & Gu, P. (2022). A hybrid model of ghost-convolution enlightened transformer for effective diagnosis of grape leaf disease and pest. *Journal of King Saud University - Computer and Information Sciences*, 34, 1755–1767.

24. McMahan, B., Moore, E., Ramage, D., Hampson, S., & y Arcas, B. A. (2017). Communication-efficient learning of deep networks from decentralized data. *Proceedings of the 20th International Conference on Artificial Intelligence and Statistics*, 1273–1282.
25. Mohanty, S. P., Hughes, D. P., & Salathé, M. (2016). Using deep learning for image-based plant disease detection. *Frontiers in Plant Science*, 7, 1419.
26. Mrisho, L. M., Mbilinyi, N. A., Ndalawha, M., Ramcharan, A. M., Kehs, A. K., McCloskey, P. C., Murithi, H., Hughes, D. P., & Legg, J. P. (2020). Accuracy of a smartphone-based object detection model, PlantVillage Nuru, in identifying the foliar symptoms of the viral diseases of cassava-CMD and CBSD. *Frontiers in Plant Science*, 11, 590889.
27. Nguyen, D. C., Ding, M., Pathirana, P. N., Seneviratne, A., Li, J., & Poor, H. V. (2021). Federated learning for internet of things: A comprehensive survey. *IEEE Communications Surveys & Tutorials*, 23, 1622–1658.
28. Noyan, M. A. (2022). Uncovering bias in the PlantVillage dataset. *arXiv preprint arXiv:2206.04374*.
29. Nutter, F. W., Teng, P. S., & Shokes, F. M. (1991). Disease assessment terms and concepts. *Plant Disease*, 75, 1187–1188.
30. Nyakuri, J. P., Nkundineza, C., Gatera, O., Nkurikiyeyezu, K., & Mwitende, G. (2025). AI and IoT-powered edge device optimized for crop pest and disease detection. *Scientific Reports*, 15, 22905.
31. Radford, A., Kim, J. W., Hallacy, C., Ramesh, A., Goh, G., Agarwal, S., & Sutskever, I. (2021). Learning transferable visual models from natural language supervision. *Proceedings of the International Conference on Machine Learning*, 8748–8763.
32. Ramcharan, A., Baranowski, K., McCloskey, P., Ahmed, B., Legg, J., & Hughes, D. P. (2017). Deep learning for image-based cassava disease detection. *Frontiers in Plant Science*, 8, 1852.
33. Redmon, J., Divvala, S., Girshick, R., & Farhadi, A. (2016). You only look once: Unified, real-time object detection. *Proceedings of the IEEE Conference on Computer Vision and Pattern Recognition*, 779–788.
34. Ren, S., He, K., Girshick, R., & Sun, J. (2017). Faster R-CNN: Towards real-time object detection with region proposal networks. *IEEE Transactions on Pattern Analysis and Machine Intelligence*, 39, 1137–1149.
35. Selvaraju, R. R., Cogswell, M., Das, A., Vedantam, R., Parikh, D., & Batra, D. (2017). Grad-CAM: Visual explanations from deep networks via gradient-based localization. *Proceedings of the IEEE International Conference on Computer Vision*, 618–626.

36. Shafik, W., Tufail, A., De Silva, L. C., Haji Mohd Apong, R. A. A., & Kim, K. H. (2025). Deep learning technique for plant disease classification and pest detection and model explainability elevating agricultural sustainability. *BMC Plant Biology*, 25, 1491.
37. Shoaib, M., Sadeghi-Niaraki, A., Ali, F., Hussain, I., & Khalid, S. (2025). Leveraging deep learning for plant disease and pest detection: A comprehensive review and future directions. *Frontiers in Plant Science*, 16, 1538163.
38. Simonyan, K., & Zisserman, A. (2014). Very deep convolutional networks for large-scale image recognition. *arXiv preprint arXiv:1409.1556*.
39. Singh, A. K., Rao, A., Chattopadhyay, P., Maurya, R., & Singh, L. (2024). Effective plant disease diagnosis using vision transformer trained with leafy-generative adversarial network-generated images. *Expert Systems with Applications*, 254, 124387.
40. Singh, D., Jain, N., Jain, P., Kayal, P., Kumawat, S., & Batra, N. (2020). PlantDoc: A dataset for visual plant disease detection. *Proceedings of the ACM IKDD CoDS and COMAD*, 249–253.
41. Thai, H. T., Le, K. H., & Nguyen, N. L. T. (2023). FormerLeaf: An efficient vision transformer for cassava leaf disease detection. *Computers and Electronics in Agriculture*, 204, 107518.
42. Too, E. C., Yujian, L., Njuki, S., & Yingchun, L. (2019). A comparative study of fine-tuning deep learning models for plant disease identification. *Computers and Electronics in Agriculture*, 161, 272–279.
43. Wang, C. Y., Bochkovskiy, A., & Liao, H. Y. M. (2023). YOLOv7: Trainable bag-of-freebies sets new state-of-the-art for real-time object detectors. *Proceedings of the IEEE/CVF Conference on Computer Vision and Pattern Recognition*, 7464–7475.
44. Wolfert, S., Ge, L., Verdouw, C., & Bogaardt, M. J. (2017). Big data in smart farming—A review. *Agricultural Systems*, 153, 69–80.

DISEASES OF JACKFRUIT (*ARTOCARPUS HETEROPHYLLUS* LAM.) AND THEIR MANAGEMENT

Vijay Kumar*¹ and Ashok Chhetri²

¹Department of Plant Pathology,

²Department of Horticulture-Fruit Science,

Multi Technology Testing Centre & Vocational Training Centre,
Lembucherra, Tripura, Central Agricultural University, Imphal, India

*Corresponding author E-mail: vnarwal777@yahoo.com

1. Introduction

Jackfruit (*Artocarpus heterophyllus* Lam.), a member of the Moraceae family, is native to India and is believed to have originated in the rainforests of the Western Ghats (Rowe-Dutton, 1985; Chauvet and Mitra, 2023). It is widely cultivated across tropical regions including Bangladesh, Myanmar, Sri Lanka, Malaysia, Indonesia, the Philippines, and Brazil. In India, jackfruit is extensively distributed in the northeastern states, the foothills of the Himalayas, and the southern and coastal regions. The crop occupies approximately 1.87 lakh hectares nationally (Anonymous, 2021), with earlier estimates indicating about 26,000 hectares under cultivation, notably in Assam (8,500 ha), Tripura (6,200 ha), Bihar (4,500 ha), and Kerala (2,200 ha).

Despite its wide distribution, jackfruit is predominantly grown in homesteads, backyards, and mixed cropping systems rather than in organized orchards. In southern India, it is commonly cultivated along the western coast in association with arecanut and coconut plantations. The species thrives in humid tropical climates, particularly on hill slopes, and is sensitive to cold, frost, and drought conditions. It is generally grown from sea level up to 1,500 m elevation in southern India and in the Himalayan foothills in northern regions (Hayes, 1966).

Botanically, jackfruit is an evergreen, medium-sized tree reaching 8-25 m in height, producing the largest edible fruits among tree species, with individual fruits weighing up to 35 kg (Shyamamma *et al.*, 2008). Cytogenetically, it is a tetraploid species ($2n = 4x = 56$) with a basic chromosome number of $x = 14$. The species exhibits substantial genetic variability due to its heterozygous nature, high cross-pollination rate, and seed-based propagation, leading to diversity in fruit characteristics such as shape, size, maturity, spine structure, latex content, flake colour, and bulb quality (Goswami *et al.*, 2011; Valeeta *et al.*, 2023; Sardar *et al.*, 2019).

Although jackfruit is nutritionally rich its pulp containing carotenoids, vitamins, and minerals (Samaddar, 1985; Narasimham, 1990), and its seeds being a good source of starch, dietary fibre, and protein (Hettiarachchi *et al.*, 2011; Swami *et al.*, 2012) its productivity remains low, and it is considered an underutilized crop. The fruit is processed into various value-added products such as chips, nectar, wine, ice cream, vinegar, preserves, and ready-to-serve beverages (Jagadeesh *et*

al., 2009). Additionally, bioactive compounds such as carotenoids and resveratrol contribute to its health benefits, including potential protection against chronic degenerative diseases (Krinsky *et al.*, 2003; Akshatha *et al.*, 2015).

However, like other perennial fruit crops, jackfruit is susceptible to a range of insect pests and diseases, which significantly affect its productivity and fruit quality. Among diseases, the most important include pink disease, fruit rot, bud rot, blossom or flower rot, and leaf spot diseases, which collectively contribute to yield losses and reduced market quality. The prevalence and severity of these diseases are often influenced by the humid climatic conditions in which jackfruit is typically grown. Despite its economic and nutritional importance, systematic research on disease resistance, molecular characterization, and screening of superior genotypes remains limited in India. This highlights the need for comprehensive studies focusing on disease incidence, pathogen diversity, and the development of resistant cultivars through molecular approaches. Overall, understanding the disease spectrum and associated factors is essential for improving jackfruit productivity and promoting its cultivation as a commercially viable fruit crop.

2. Major Diseases of Jackfruits

2.1 Stem and fruit rots

2.1.1. Etiology

Rhizopus rot is one of the most destructive diseases of jackfruit, primarily caused by *Rhizopus artocarp*, along with other species of the genus *Rhizopus* (Nelson, 2005). The pathogen is a fast-growing, saprophytic and opportunistic fungus that infects tender plant tissues, particularly inflorescences and young fruits. Although *Rhizopus* spp. are commonly associated with fruit rots in several crops, including peach, papaya, and tomato (Murad and Zainudin, 2017; Ghosh *et al.*, 2015), the jackfruit pathogen is specifically adapted to humid tropical conditions. The fungus produces abundant sporangiospores, which facilitate rapid dissemination and infection.

2.1.2 Symptoms

The disease initially manifests as soft, watery, brown lesions on flowers and young fruits. As the infection progresses, these lesions enlarge and become covered with a characteristic cottony growth of white mycelia, followed by the development of black, powdery sporangia on the surface. Infected fruits turn black, rot extensively, shrink, and may become mummified. The pathogen can invade entire inflorescences, leading to complete rotting and eventual abscission. Severe infection results in premature fruit drop, significantly reducing yield.

2.1.3. Epidemiology

Rhizopus rot is favoured by warm and humid environmental conditions, which promote rapid fungal growth and spore production. High relative humidity, dense canopy, and poor air circulation enhance disease incidence and spread. The pathogen survives on decaying organic matter and infected plant debris, serving as a primary inoculum source. Infection is most severe

during the flowering and early fruit development stages. Surveys have indicated that up to 80% of growers in affected areas experience problems with this disease, with reported crop losses ranging from 15% to 32% (Murad and Zainudin, 2017; Nelson, 2005).

2.1.4. Management

Effective management of Rhizopus rot involves an integrated approach combining cultural and chemical measures:

- **Cultural practices:**
 - Regular removal and destruction of diseased fruits from both the tree and ground to minimize inoculum load.
 - Sanitation through cleaning of decaying organic debris around the tree.
 - Pruning to improve canopy aeration and reduce humidity levels.
- **Chemical control:**
 - Application of fungicides such as copper hydroxide (53%), Bordeaux mixture (0.5–1.0%), copper oxychloride (0.2–0.25%), and 2,6-dichloro-4-nitroaniline (DCNA) 75 WP has been recommended (Azad, 2000; Ghosh, 1994; McMillan, 1974).
 - Spraying during the early fruiting stage at three-week intervals, particularly from January to March, using captan (0.2%), Bordeaux mixture (1.0%), or copper oxychloride (0.25%) has been found effective in controlling the disease.

2.2 Fruit bronzing

2.2.1. Etiology

Fruit bronzing of jackfruit is a bacterial disease caused by *Pantoea stewartii* (Mergaert *et al.*, 2015). The pathogen is known to infect a wide range of host plants including pepper, tomato, strawberry, and maize, indicating its broad host adaptability (Cluever *et al.*, 2015; Gapasin *et al.*, 2014; Mergaert *et al.*, 2015). The disease has been formally reported in jackfruit from Mexico and the Philippines (Hernández-Morales *et al.*, 2017; Gapasin *et al.*, 2014).

2.2.2. Symptoms

The characteristic symptom of fruit bronzing is the development of reddish to bronze discoloration in the fruit pulp and rags. This internal discoloration significantly reduces the visual and market quality of the fruit, making it less acceptable to consumers (Ibrahim *et al.*, 2019). Infected fruits may appear externally normal in early stages, but upon cutting, the affected tissues show uneven pigmentation and quality deterioration.

2.2.3. Epidemiology

The development and severity of fruit bronzing are closely associated with environmental factors, particularly high relative humidity. Warm and humid conditions favor bacterial multiplication and disease expression. Dense canopy structure and poor air circulation create microclimatic conditions conducive to disease development. The pathogen may spread through

contaminated plant materials and possibly through wounds or natural openings in developing fruits.

2.2.4. Management

Management of fruit bronzing primarily relies on cultural practices aimed at modifying the microclimate and reducing disease-conducive conditions:

- **Canopy management:** Regular pruning and training of jackfruit trees to improve air circulation and reduce humidity within the canopy.
- **Environmental regulation:** Maintaining optimal temperature and reducing relative humidity around the plant to limit bacterial growth and infection.
- **Orchard sanitation:** Removal of infected plant parts and maintenance of field hygiene to reduce inoculum sources.

2.3. Leafspot

2.3.1. Etiology

Leaf spot of jackfruit is a complex disease caused by several fungal pathogens, including *Phomopsis artocarpina*, *Pestalotia quepini*, *Colletotrichum lagenarium*, and *Septoria artocarpi*. Among these, *Phomopsis artocarpina* is considered a major causal organism responsible for severe infections in jackfruit trees (Elevitch and Manner, 2006b). The disease is often associated with gummosis symptoms, particularly in severe cases (Rahman and Afroz, 2016).

2.3.2. Symptoms

The disease manifests primarily as spots on leaves, stems, and branches. Infected tissues initially develop brown lesions that gradually enlarge, leading to drying and necrosis. In severe cases, the affected tissues die, causing dieback of branches. The infected trees become weak, showing reduced vigor and timber quality. The disease may also predispose trees to secondary insect infestations.

2.3.3. Epidemiology

Leaf spot disease is favored by warm and humid environmental conditions, particularly during the rainy season. High moisture levels promote fungal growth, spore germination, and disease spread. The pathogens survive in infected plant debris and are disseminated through wind, rain splash, and possibly insect activity. Disease incidence in jackfruit trees has been reported to range from 45% to 87% in affected areas, especially when associated with gummosis caused by *Phomopsis artocarpina* (Rahman and Afroz, 2016).

2.3.4. Management

Management of leaf spot involves both cultural and chemical measures:

- **Cultural practices:**
 - Removal and destruction of infected plant parts to reduce inoculum load.
 - Maintenance of orchard sanitation and proper spacing to improve air circulation.

- **Chemical control:**

- Application of Bordeaux paste or coal tar on affected areas has been reported to be effective (Rahman and Afroz, 2016).
- Treatments applied before or after the rainy season have shown better efficacy, as excessive moisture during rains may reduce treatment effectiveness.
- These measures have been reported to control up to 90% of leaf spot incidence under field conditions.

2.4. Dieback

2.4.1. Etiology

Dieback of jackfruit is primarily caused by the fungal pathogen *Colletotrichum gloeosporioides*, a widely distributed species responsible for several diseases in fruit crops (Awasthi *et al.*, 2005). Some places *Botryodiplodia theobromae* fungus reported for the cause of disease. The disease has been reported in jackfruit plantations of Mymensingh and Gazipur districts. In addition to field infections, post-harvest deterioration of jackfruit has also been associated with fungal pathogens, particularly species of *Aspergillus* and *Penicillium*. Among these, *Aspergillus niger* has been confirmed as a pathogenic species causing fruit spoilage (Juan *et al.*, 2011).

2.4.2. Symptoms

The disease is characterized by progressive drying and death of twigs, branches, and terminal shoots, leading to dieback symptoms. Initially, infected portions show necrosis, which gradually extends backward from the tip, causing drying of affected tissues. In severe cases, entire branches may die, weakening the tree. The disease may also be associated with secondary infections and pest infestations, particularly borers, which further aggravate tissue damage. Post-harvest, infected fruits deteriorate rapidly, with a shelf life of only 2–3 days due to fungal decay (Juan *et al.*, 2011).

2.4.3. Epidemiology

The disease is favoured by warm and humid environmental conditions, which promote fungal growth and infection. The pathogen spreads through spores disseminated by wind, rain splash, and infected plant materials. Wounds caused by insect pests, especially borers, facilitate pathogen entry and increase disease severity. Poor orchard sanitation and inadequate management practices further enhance disease incidence. Post-harvest losses are significant due to rapid colonization of fruits by pathogenic fungi under ambient storage conditions (Khan *et al.*, 2020).

2.4.4. Management

An integrated approach combining cultural, mechanical, and chemical measures is recommended for effective management:

- **Cultural and mechanical practices:**

- Pruning and removal of infected twigs and branches to prevent disease spread.

- Scraping out borer-damaged portions followed by application of lime paste to affected areas to check further infection.
- Maintenance of orchard sanitation and proper plant care.
- **Chemical control:**
 - Application of Bordeaux mixture (0.5%) as a paste on infected portions, followed by sealing with mud to prevent pathogen entry.
 - Spraying of systemic fungicides such as carbendazim (0.1%), thiophanate methyl (0.2%), or chlorothalonil (0.2%) has been reported to be effective (PAT, 2012).

2.5. Gummosis

2.5.1. Etiology

Gummosis of jackfruit is caused by the fungal pathogen *Phomopsis artocarp*i. It is a widespread and economically important disease reported in jackfruit-growing regions, particularly in Bangladesh. The pathogen is also associated with other symptoms such as leaf spot under certain conditions, though with comparatively less damage in some regions (Elevitch and Manner, 2006b).

2.5.2. Symptoms

The disease primarily affects the stem and branches. Initial symptoms include the formation of small splits or cracks in the bark at the site of infection. From these lesions, a characteristic brown, gummy exudate oozes out, which often attracts various insects. As the disease progresses, the affected tissues weaken, leading to reduced structural integrity of the tree. Severe infections result in decline of plant vigor, reduction in timber quality, and decreased fruit yield. In advanced stages, the overall lifespan of the tree may be significantly shortened.

2.5.3. Epidemiology

Gummosis is prevalent across different age groups of jackfruit trees, with reported infection levels ranging from 45% to 87% in Bangladesh (Rahman and Afroz, 2016). The disease is favored by humid environmental conditions and poor orchard management practices. The pathogen survives in infected plant tissues and spreads through wounds, cracks, and possibly through insect activity. The disease was first reported in Narasingdhi in 2006 and has since become a common constraint in jackfruit production.

2.5.4. Management

Effective management of gummosis involves a combination of mechanical and chemical measures:

- **Mechanical control:**
 - Chiseling or scraping of infected bark tissues to remove diseased portions.
 - Proper cleaning of the affected area before treatment application.

- **Chemical control:**

- Application of Bordeaux paste or coal tar on the chiseled areas to prevent further infection (Rahman and Afroz, 2016).
- Use of fungicides such as Bordeaux mixture and Ridomyl Gold has also been reported to be effective against associated fungal pathogens.

2.6. Anthracnose

2.6.1. Etiology

Anthracnose of jackfruit is caused by the fungal pathogen *Colletotrichum gloeosporioides*, a widely distributed and economically important pathogen affecting many tropical fruit crops. The fungus infects multiple plant parts, including leaves, stems, and fruits, leading to significant yield and quality losses.

2.6.2. Symptoms

The disease is characterized by the appearance of dark, sunken lesions on leaves, which may enlarge and coalesce under severe infection. On stems, the pathogen causes cankers that may lead to dieback of twigs and branches. In fruits, symptoms include dark, circular, sunken spots that gradually expand, resulting in fruit rot. Under favorable conditions, the lesions may produce masses of fungal spores, further aiding disease spread.

2.6.3. Epidemiology

Anthracnose thrives under warm and humid environmental conditions, which favor fungal growth, sporulation, and infection. High relative humidity, frequent rainfall, and poor air circulation within dense canopies enhance disease development. The pathogen spreads through spores disseminated by rain splash, wind, and contaminated plant materials. Infection can occur at various stages of plant growth, including post-harvest under suitable storage conditions.

2.6.4. Management

Effective management of anthracnose involves an integrated approach:

- **Cultural practices:**

- Maintenance of orchard sanitation by removing and destroying infected plant parts.
- Pruning to improve air circulation and reduce canopy humidity.
- Proper spacing and management to minimize moisture retention.

- **Chemical control:**

- Preventive application of fungicides, particularly copper-based compounds, to protect susceptible plant parts.
- Timely spraying during favorable environmental conditions to reduce infection and disease spread.

2.7. Phytophthora Root Rot

2.7.1. Etiology

Phytophthora root rot is a destructive soil-borne disease of jackfruit caused by several species of the genus *Phytophthora*. These pathogens are oomycetes (water molds) that thrive in moist soil conditions and infect plant roots, leading to severe decline in tree health.

2.7.2. Symptoms

The disease primarily affects the root system, causing root decay and rotting. Infected trees exhibit symptoms such as wilting, yellowing of leaves, stunted growth, and gradual decline. As the disease progresses, feeder roots are destroyed, impairing water and nutrient uptake. In severe cases, extensive root damage leads to dieback of the canopy and eventual death of the tree.

2.7.3. Epidemiology

Phytophthora root rot is favored by poorly drained soils and waterlogged conditions. High soil moisture facilitates the production and movement of zoospores, which infect roots. The pathogen survives in soil and infected plant debris for extended periods. Disease spread occurs through irrigation water, contaminated soil, and infected planting materials. Warm and humid environments further enhance disease development.

2.7.4. Management

Management of Phytophthora root rot relies on an integrated approach:

- **Cultural practices:**
 - Improving soil drainage to prevent water stagnation.
 - Avoiding over-irrigation and waterlogging conditions.
 - Planting in well-drained soils and using raised beds where necessary.
 - Removal and destruction of severely infected plants to reduce inoculum.
- **Chemical control:**
 - Application of systemic fungicides effective against oomycetes (e.g., fungicides containing metalaxyl or similar active ingredients) to protect roots from infection.
 - Soil drenching around the root zone for better efficacy.

2.8. Powdery Mildew

2.8.1. Etiology

Powdery mildew of jackfruit is caused by fungi belonging to the genus *Oidium*, which are obligate parasites commonly infecting aerial plant parts. The pathogen primarily colonizes leaf surfaces and young shoots, deriving nutrients from host tissues.

2.8.2. Symptoms

The disease is characterized by the appearance of white, powdery patches on leaves, tender shoots, and sometimes inflorescences. As the infection progresses, these patches may enlarge and coalesce, covering large portions of the leaf surface. Severely infected leaves may become

distorted, curl, and eventually undergo premature senescence and drop. Young shoots may also exhibit reduced growth and vigor.

2.8.3. Epidemiology

Powdery mildew develops under moderate temperature and high humidity conditions, although free water is not essential for infection. Dense canopy, poor air circulation, and shaded environments favor disease development. The pathogen spreads through airborne conidia, enabling rapid dissemination under conducive conditions.

2.8.4. Management

Effective management of powdery mildew involves integrated cultural and chemical approaches:

- **Cultural practices:**
 - Maintaining proper spacing between trees to improve air circulation.
 - Pruning dense canopy to reduce humidity and enhance sunlight penetration.
- **Chemical control:**
 - Application of fungicides such as sulphur or potassium bicarbonate at the initial stages of infection.
 - Timely and repeated sprays under favourable conditions to prevent disease spread.

2.9. Pink Disease of Jackfruit

2.9.1. Etiology

Pink disease of jackfruit is caused by the fungal pathogens *Botryobasidium salmonicolor* and its anamorph *Corticium salmonicolor*. These fungi infect woody tissues, particularly branches and stems, and are commonly associated with dieback in several tropical tree crops.

2.9.2. Symptoms

The disease is characterized by the appearance of pink to salmon-colored fungal growth on infected branches and trunks. Initially, a thin, pinkish, powdery coating develops on the bark surface. As the infection progresses, the affected areas may become encrusted with fungal growth. In young branches, the disease leads to dieback, while severe infections result in premature leaf fall and decline in plant vigor. In advanced stages, extensive branch mortality may occur.

2.9.3. Epidemiology

Pink disease is favored by warm, humid, and rainy environmental conditions. High moisture levels facilitate fungal growth and sporulation. The pathogen spreads through wind, rain splash, and insect activity, which help dislodge and disseminate fungal propagules. Dense canopy and poor air circulation further enhance disease development and spread.

2.9.4. Management

Management of pink disease involves a combination of cultural and chemical practices:

- **Cultural practices:**
 - Regular inspection and early detection of infected branches.
 - Pruning and destruction of infected plant parts to reduce inoculum.
 - Maintaining proper canopy structure to improve air circulation and reduce humidity.
- **Chemical control:**
 - Application of copper-based fungicides, particularly copper oxychloride, on freshly cut surfaces after pruning to prevent further infection.

2.10 Sooty Mold

2.10.1. Etiology

Sooty mold is a secondary fungal problem associated with the growth of saprophytic fungi on honeydew secreted by sap-sucking insects such as aphids, whiteflies, and mealybugs. The fungi do not directly infect plant tissues but colonize the sugary exudates deposited on leaf and fruit surfaces. Thus, the primary cause of the condition is insect infestation, while the black fungal growth represents a secondary development.

2.10.2. Symptoms

The disease is characterized by the presence of black, soot-like fungal growth on leaves, stems, and sometimes fruits. The affected surfaces appear as if covered with charcoal or black dust. In severe cases:

- Leaves become dull, sticky, and coated with black deposits.
- Reduction in photosynthesis due to blockage of sunlight.
- Yellowing, curling, and premature leaf drop.
- Poor fruit development and reduced tree vigor.
- Presence of ants, which are attracted to honeydew and often indicate infestation.

Although the fungus does not penetrate plant tissues, heavy colonization interferes with physiological processes, leading to overall decline in plant health.

2.10.3. Epidemiology

Sooty mold development is closely linked to the population dynamics of sap-sucking insects. Warm and humid conditions favor both insect multiplication and fungal growth. Dense canopy, poor air circulation, and neglected orchard sanitation further enhance disease incidence. The fungi grow rapidly on honeydew deposits, spreading across plant surfaces under favorable environmental conditions.

2.10.4. Management

Management of sooty mold focuses primarily on controlling the associated insect pests and improving orchard hygiene:

- **Control of insect vectors:**
 - Application of neem oil sprays or mild soap solutions to reduce populations of aphids, whiteflies, and mealybugs.

- Spraying should cover both upper and lower leaf surfaces where insects reside
- **Physical removal:**
 - Washing or gently wiping affected leaves with water to remove fungal deposits, especially in small trees or early infestations
- **Cultural practices:**
 - Pruning heavily infested branches to prevent spread.
 - Improving air circulation through proper canopy management.
 - Maintaining field sanitation and removing plant debris.
- **Monitoring:**
 - Regular inspection of leaves, particularly the undersides, for early detection of insect infestation.
 - Prompt action when honeydew or insect presence is observed.

Sooty mold itself is not directly pathogenic but serves as an indicator of underlying pest problems. Effective insect management is therefore essential to prevent its occurrence and to maintain healthy jackfruit trees.

2.11. Bacterial Leaf Spot

2.11.1. Etiology

Bacterial leaf spot of jackfruit is caused by *Xanthomonas campestris*, a gram-negative, rod-shaped bacterium that infects foliar tissues. Unlike fungal pathogens, this bacterium multiplies rapidly under favorable environmental conditions and spreads through water, tools, and human activity. It enters the plant through natural openings such as stomata or through wounds created during pruning or mechanical injury.

2.11.2. Symptoms

Initial symptoms appear as small, dark, water-soaked lesions on the leaf surface. As the disease progresses, these lesions enlarge and are often surrounded by characteristic yellow halos, giving a bullseye appearance. Infected leaves gradually curl, dry, and undergo premature abscission. Severe infection leads to significant defoliation, resulting in a sparse, patchy canopy and reduced photosynthetic capacity of the tree.

2.11.3. Epidemiology

The disease is favored by warm and humid environmental conditions, particularly during the rainy or monsoon season. High moisture facilitates bacterial multiplication and dispersal. The pathogen spreads through:

- Splashing rainwater and irrigation water
- Contaminated pruning tools and equipment
- Human handling and field operations

Dense planting, poor air circulation, and overhead irrigation create a conducive microclimate for disease development. The bacterium can survive in infected plant debris and may also be introduced through contaminated planting materials.

2.11.4. Management

Effective management of bacterial leaf spot requires an integrated approach focusing on prevention and sanitation:

- **Use of healthy planting material:**
 - Plant disease-free seedlings obtained from certified nurseries.
- **Sanitation measures:**
 - Disinfect pruning tools before and after use using 10% bleach solution or alcohol.
 - Remove and destroy infected leaves and plant parts; avoid composting infected material.
- **Cultural practices:**
 - Prune trees to improve air circulation and reduce canopy humidity.
 - Avoid dense planting and maintain proper spacing.
 - Minimize leaf wetness by avoiding overhead irrigation; adopt drip irrigation where possible.
 - Maintain field hygiene by controlling weeds and removing plant debris.
- **Chemical control:**
 - Application of copper-based bactericides such as copper hydroxide or copper oxychloride can help suppress disease development when applied at early stages.
 - Sprays should be applied during low-temperature periods (morning or evening) for better effectiveness.
- **Monitoring and preventive care:**
 - Regular inspection of orchards, especially after rainfall, to detect early symptoms.
 - Timely intervention to prevent rapid spread of the pathogen.

References

1. Akshatha, S., Anbarasu, K., & Vijayalakshmi, G. (2015). Resveratrol content and antioxidant properties of underutilized fruits. *Journal of Food Science and Technology*, 52(1), 383–390.
2. Anonymous. (2021). *Horticultural statistics at a glance*. Department of Agriculture & Farmer's Welfare, Ministry of Agriculture & Farmer's Welfare, Government of India, New Delhi.
3. Awasthi, D. P., Sarkar, S., Mishra, N. K., & Kaisar, S. (2005). Disease situation of some major fruit crops in new alluvial plains of West Bengal. *Environment and Ecology*, 23(3), 497–499.
4. Azad, A. K. (2000). *Genetic diversity of jackfruit in Bangladesh and development of propagation methods* (Ph.D. thesis). University of Southampton, UK.

5. Chauvet, M., & Mitra, S. (2023). Jackfruit: Botany, origin, history and production. In S. Mitra (Ed.), *Jackfruit: Botany, production and uses* (pp. 1–19). CAB International.
6. Cluever, J. D., Smith, H. A., Funderburk, J. E., & Frantz, G. (2015). Thrips in Florida strawberry crops. *University of Florida IFAS Extension*, 1–9.
7. Elevitch, C. R., & Manner, H. I. (2006). *Species profiles for Pacific Island agroforestry: Artocarpus heterophyllus (jackfruit)*.
8. Gapasin, R. M., Garcia, R. P., Christine, T., Cruz, C. S., & Borines, L. M. (2014). Fruit bronzing: A new disease affecting jackfruit caused by *Pantoea stewartii*. *Annals of Tropical Research*, 36(1), 17–31.
9. Ghosh, G. H. (1994). Studies on flowering and prevalence of fruit drop in jackfruit. *Horticulture Annual Report (1993–94)*, BARI, Gazipur, Bangladesh, 4–9.
10. Ghosh, R., Barman, S., Mukhopadhyay, A., & Mandal, N. C. (2015). Biological control of fruit rot of jackfruit by rhizobacteria and food-grade lactic acid bacteria. *Biological Control*, 83, 29–36.
11. Goswami, C., Hossain, M. A., Kader, H. A., & Islam, R. (2011). Assessment of physicochemical properties of jackfruit (*Artocarpus heterophyllus* Lam.) pulp. *Journal of Horticulture and Forestry Biotechnology*, 15, 26–31.
12. Hayes, W. B. (1966). *Fruit growing in India*. Kitabistan, Allahabad.
13. Hernández-Morales, A., Pérez-Casillas, J. M., Soria-Guerra, R. E., Velázquez-Fernández, J. B., & Arvizu-Gómez, J. L. (2017). First report of *Pantoea stewartii* subsp. *stewartii* causing jackfruit bronzing disease in Mexico. *Plant Disease*, 99, 799–818.
14. Hettiarachchi, U. P. K., Ekanayake, S., & Welihinda, J. (2011). Nutritional assessment of jackfruit (*Artocarpus heterophyllus* L.) meal. *Ceylon Medical Journal*, 56(2), 54–58. <https://doi.org/10.4038/cmj.v56i2.3109>
15. Ibrahim, R., Ismail-Suhaimy, N. W., Shu-Qing, T., Ismail, S. I., & Abidin, N. (2019). Molecular characterization and phylogenetic analysis of *Pantoea stewartii* subsp. *stewartii* causing bronzing disease of jackfruit. *Journal of Plant Pathology*.
16. Jagadeesh, S. L., Reddy, B. S., Hegde, L. N., Swamy, G. S. K., & Raghavan, G. S. V. (2006). Value addition in jackfruit (*Artocarpus heterophyllus* Lam.).
17. Juan, F., Gómez, L., Juan, A. R. S., Alika, G. E., Guadalupe, L. S., & Montserrat, C. S. (2011). Postharvest fungal pathogens of jackfruit. *Revista Mexicana de Micología*, 34, 9–15.
18. Khan, A. U., Khan, A. U., Khanal, S., & Gyawali, S. (2020). Insect pests and diseases of cinnamon (*Cinnamomum verum*) and their management in agroforestry systems: A review. *Acta Entomology and Zoology*, 1(2), 51–59.

19. Krinsky, N. I., Landrum, J. T., & Bone, R. A. (2003). Biologic mechanisms of the protective role of lutein and zeaxanthin in the eye. *Annual Review of Nutrition*, 23, 171–201. <https://doi.org/10.1146/annurev.nutr.23.011702.073307>
20. McMillan, R. T. (1974). Rhizopus artocarpi rot of jackfruit (*Artocarpus heterophyllus*). *Proceedings of the Florida State Horticultural Society*, 392–393.
21. Mergaert, S., Gapasin, R. M., Garcia, R. P., & Christine, T. (2015). Fruit bronzing: A new disease affecting jackfruit caused by *Pantoea stewartii*. *Annals of Tropical Research*, 36(1), 17–31.
22. Murad, N. B. A., & Zainudin, N. (2017). Review of fruit rot diseases of important tropical and some temperate fruit crops. *Journal of Agriculture and Veterinary Science*, 3, 138–156.
23. Narasimham, P. (1990). Breadfruit and jackfruit. In S. Nagy, P. E. Shaw, & W. F. Wardowski (Eds.), *Fruits of tropical and subtropical origin* (pp. 93–259). Florida Science Source.
24. Nelson, S. (2005). *Rhizopus rot of jackfruit*. *Plant Disease*, PD 29. Pal, K. K., & Gardener, B. M. (2006). Biological control of plant pathogens. *Plant Health Instruction*.
25. PAT. (2012). Dieback of jackfruit. Retrieved June 16, 2012, from <http://ecourses.online.iasri.res.in/mod/page/view.php?id=905>
26. Rahman, M. A., & Afroz, M. (2016). Survey on diseases of jackfruit and control measures for gummosis in Bangladesh. *Eco-friendly Agriculture Journal*, 9(2), 10–14.
27. Rowe-Dutton, P. (1985). *Artocarpus heterophyllus* (jackfruit). In R. J. Garner & S. A. Chaudhuri (Eds.), *The propagation of tropical fruit trees* (pp. 269–290). FAO & Commonwealth Bureau of Horticulture.
28. Samaddar, H. M. (1985). Jackfruit. In T. K. Bose & S. K. Mishra (Eds.), *Fruits of India: Tropical and subtropical* (pp. 638–649). Naya Prokash.
29. Sardar, A. S., Modak, A., Das, L., Pal, P. K., Nain, M. S., Panda, S., & Mondal, S. (2019). Perceptual characterization for quality assessment of jackfruit in Terai districts of West Bengal. *Indian Journal of Agricultural Sciences*, 89, 433–438.
30. Shyamamma, S., Chandra, S. B. C., Hegde, M., & Narayanaswamy, P. (2008). Genetic diversity in jackfruit based on AFLP markers. *Genetics and Molecular Research*, 7(3), 645–656.
31. Swami, S. B., Thakor, N. J., Haldankar, P. M., & Kalse, S. B. (2012). Jackfruit and its functional components related to human health: A review. *Comprehensive Reviews in Food Science and Food Safety*, 11, 565–576.
32. Valeeta, M. D., Shyamamma, S., Kalpana, B., & Nagesha, S. N. (2023). Morphometric evaluation of jackfruit accessions for fruit and flake quality traits. *Mysore Journal of Agricultural Sciences*, 57, 388–398.

MODERN DIAGNOSTIC TOOLS AND BIOMARKERS RELATED TO ANIMAL REPRODUCTION TECHNOLOGIES

Aashish*¹, Ravi Kumar Yadav² and Ashok Kumar³

¹Department of Veterinary Gynaecology and Obstetrics,

M. R. Veterinary College & Research Center, Jhajjar, Haryana, India

²ICAR-Indian Veterinary Research Institute (IVRI), Izatnagar, Bareilly, UP, India

³College of Veterinary and Animal Science, Navania, Vallabh Nagar, Udaipur, India.

*Corresponding author E-mail: aashishdhull1998@gmail.com

Introduction

Overall animal health, productivity as well as fertility decrease due to reproductive diseases which constrain animal production. Conditions such as endometritis, metritis, vaginitis, cervicitis, salpingitis, retained placenta, purulent vaginal discharge (PVD), repeat breeding and bovine genital campylobacteriosis are associated with reproductive failure and leads to a economic losses. The economic loss associated with reproductive diseases and disorders in cattle is very high. Thus, there is requirement for effective diagnostic and predictive strategies to understand the complex molecular mechanisms underlying reproductive diseases. Conventional diagnostic approaches have traditionally relied on clinical examination, targeted gene expression, protein detection and microbial identification. Techniques such as reverse transcriptase polymerase chain reaction, ELISA, Western blotting, flow cytometry and targeted 16S rRNA sequencing have been extensively employed. Although these techniques are valuable, they are generally target-specific and may require considerable time and labour. The emergence of Infrared thermography (IRT), Reproductive ultrasonography as well as high-throughput molecular technologies like multiomics can enable the identification of disease-associated early molecular and pathological changes. Therefore, it's important to develop the techniques as well as biomarkers which helps us to identify these disorders easily in female cattle and bulls in case of reproductive diseases.

Infrared thermography (IRT)

Infrared thermography (IRT) is an emerging, non-invasive and non-contact diagnostic technology in veterinary reproduction. It detects variations in infrared radiation emitted from the animal body surface which reflect changes in blood circulation, metabolism and tissue function. Because inflammatory and other pathological processes alter local blood perfusion and consequently surface temperature, thermographic patterns can provide objective information about physiological and pathological conditions. Thermography is generally more useful as a screening or preventive diagnostic tool with conventional reproductive examination required for

confirmation when necessary. IRT also shows promise for the early detection of reproductive disorders. In females, variations in the temperature of the external genitalia have been associated with ovarian dysfunction, hypogonadism, follicular cystic changes, vestibulovaginitis and metritis. In inflammatory conditions, increased local temperature and characteristic hyperthermic patterns are observed because of increased blood perfusion.

In males thermography is particularly relevant for evaluating scrotal and testicular thermoregulation which is essential for normal spermatogenesis. Bulls and other males with testicular dystrophy or hypogonadism show reduced temperature gradients and abnormal thermal patterns whereas inflammatory conditions such as orchitis and balanoposthitis produce increased scrotal or testicular temperatures. Thus, thermography may serve as an additional screening method for assessing testicular function and detecting andrological abnormalities.

Overall, infrared thermography offers important advantages including non-invasiveness, safety, rapidity, remote assessment and minimal animal handling. It can contribute to early or preclinical detection of reproductive abnormalities and improve reproductive monitoring.

Reproductive Ultrasonography

Reproductive ultrasonography is an important, safe and non-invasive imaging technique used for reproductive assessment in domestic animals. Since its introduction for early pregnancy diagnosis in livestock its applications have expanded to ovarian evaluation, fetal viability and diagnosis of reproductive disorders.

Ultrasonography uses different modes, including A-mode, B-mode, M-mode, and Doppler, each providing specific diagnostic information. It can detect conditions such as endometritis and pyometra. Doppler ultrasonography additionally allows assessment of blood flow while M-mode is useful for evaluating fetal cardiac activity. Despite being compact, affordable, reliable and clinically useful reproductive ultrasonography remains underutilized beyond routine pregnancy diagnosis, largely because of limited practitioner expertise. Overall it significantly improves early pregnancy diagnosis, fetal monitoring, and reproductive disorder management, although further research is suggested regarding its long-term biological effects.

Biomarker Detection

Traditional biomarker approaches involve the targeted assessment of genes, proteins or microbial genomic regions. Targeted gene expression has commonly been investigated using RT-PCR, qRT-PCR and microarray techniques, whereas protein biomarkers have been evaluated using ELISA, Western blotting and flow cytometry. Targeted amplicon sequencing, particularly 16S rRNA-based analysis, has also been used extensively to investigate the reproductive tract microbiome. These approaches remain important because they provide focused and relatively well-established methods for validating candidate biomarkers. The principal limitation of targeted approaches is that they depend on previously selected targets. Consequently,

biologically important molecules that have not been anticipated may remain undetected. Modern omics approaches address this limitation by enabling broad and relatively unbiased investigation of molecular changes associated with disease.

Transcriptomics and MicroRNAomics

Transcriptomics examines the complete set of RNA transcripts within a biological sample. RNA sequencing can provide information on messenger RNA, alternative splice variants, small RNAs and microRNAs and can therefore provide insights into gene regulation and functional pathways involved in disease. Unlike targeted RT-PCR and microarray approaches, RNA sequencing can identify sequences without requiring each target to be predetermined. Transcriptomic alterations have been associated with bovine reproductive diseases, particularly endometritis. Subclinical endometritis has been associated with distinct mRNA expression patterns in blood and endometrium. Bacterial infection has also been reported to alter uterine tissue transcriptomes and pregnancy-related gene expression, potentially contributing to infertility.

MicroRNAomics represents another emerging area. MicroRNAs regulate gene expression post-transcriptionally and participate in immune and inflammatory pathways. Differentially expressed miRNAs have been identified in exosomes obtained from cows with endometritis. Among these, bta-miR-708, bta-miR-91b and other miRNAs showed altered expression patterns compared with healthy cows. Exosomal miR-218 has also been reported to regulate bovine endometritis through the TGIF2/TGF- β pathway. The investigation of downstream targets of disease-associated miRNAs and their effects on inflammatory pathways may provide further insight into disease mechanisms and facilitate the identification of additional diagnostic and therapeutic biomarkers.

Proteomics and Protein Biomarkers

Proteomics enables investigation of the protein complement of cells, tissues and biological fluids. It includes protein abundance, structure, function, interactions and modifications. Advances in chromatography and mass spectrometry have increased the accessibility of proteomic investigations and expanded their application to disease biomarker discovery.

Protein-based biomarkers associated with bovine reproductive diseases include cytokines, acute-phase response proteins and other proteins involved in inflammatory and cellular processes. Serum amyloid A (SAA) and haptoglobin (HP) are particularly important acute-phase proteins associated with reproductive health and inflammation. Increased concentrations of HP and SAA have been reported in endometritis, metritis, purulent vaginal discharge and retained placenta. SAA has been highlighted as an emerging biomarker for endometritis because of its association with disease severity. However, HP and SAA have demonstrated relatively low sensitivity (<50%) but high specificity (>90%) for determining reproductive disease status. Other proteins reported as potential diagnostic markers for bovine endometritis include desmin, α -actin-2, heat shock protein 27, MHC class I heavy chain, transferrin, KCTD11 and ceruloplasmin. Serum fibrinogen has been identified as a predictive biomarker for bovine metritis. Thus, these

biomarkers help in identification of the disease easily and early although more studies need to be done.

Cytokines, Chemokines and Adipokines as Biomarkers

Inflammatory responses represent an important component of bovine reproductive disease. Investigated biomarkers associated with complex signalling process involves bacterial recognition Toll-like receptors, tumour necrosis factor- α and other inflammatory mediators. Cytokines participate in initiation and regulation of inflammatory responses and recruitment of immune cells to the site of infection. Several cytokines have been associated with reproductive disease. Increased expression of IL-4, IL-1 β and TNF α has been reported in cows with clinical endometritis, while IL-1 β , IL-6, IL-8 and TNF α have been associated with clinical and subclinical endometritis. IL-8, IL-1 β and CD14 have been associated with salpingitis, whereas IL-1 and IL-8 have been associated with cervicitis. Alterations in IL-2, IL-4, IL-8 and IL-10 have also been reported in association with retained placenta.

Adipokines, including adiponectin, chemerin and visfatin, have also emerged as potential biomarkers because of their involvement in reproductive function and immunity. Increased adiponectin concentrations in plasma and uterine fluid were reported to differentiate healthy cows from cows with persistent subclinical endometritis at different postpartum time points.

Acute-Phase Response Proteins

Acute-phase response proteins are produced in response to inflammation, tissue injury, infection and immune disturbances and are stimulated by pro-inflammatory cytokines. Among these proteins, SAA and HP have been most frequently investigated in bovine reproductive diseases. Increased HP and SAA concentrations have been reported in several postpartum reproductive disorders. Their potential value lies in their relationship with systemic inflammatory responses. However, their relatively low sensitivity indicates that individual biomarkers may not be sufficient for reliable disease classification. This supports the need for the development and validation of biomarker combinations and integrated diagnostic approaches.

Exosomal Biomarkers

Exosomes are small extracellular vesicles derived from endosomal compartments and are present in various body fluids. They can reflect cellular processes including immune regulation, signal transmission, antigen presentation and inflammation. Their molecular contents therefore provide an opportunity for investigating disease-associated changes through relatively accessible biological samples. Altered exosomal proteins have been identified in cows with uterine infection, highlighting their potential for early detection of reproductive disease and non-invasive diagnosis. Uterus-derived exosomes and their transcriptomic contents have also been associated with pregnancy and embryo development under endometritis conditions. The identification of differentially expressed exosomal miRNAs further demonstrates the potential of extracellular vesicles as a source of reproductive disease biomarkers. Continued investigation of their

molecular cargo may improve understanding of inflammatory pathways and provide new diagnostic and therapeutic targets.

Metabolomics and Metabolic Biomarkers

Metabolomics provides an opportunity to identify and quantify large numbers of known and unknown metabolites using small sample volumes. Unlike genomic approaches, metabolomics provides information about biochemical activity and therefore can link molecular alterations more directly with disease phenotypes. Mass spectrometry and nuclear magnetic resonance-based approaches have facilitated investigation of metabolic changes associated with reproductive diseases.

Metabolic inflammation and inadequate adaptation to postpartum metabolic requirements may contribute to bacterial proliferation and immune activation. Increased serum non-esterified fatty acids and β -hydroxybutyrate at two weeks postpartum have been identified as early indicators of systemic inflammation in cows with subclinical endometritis, purulent vaginal discharge and metritis. Increased antepartum superoxide dismutase activity has also been identified as a predictive biomarker for retained placenta. Plasma metabolic biomarkers have demonstrated the ability to predict periparturient diseases several weeks before their development, with reported sensitivity of 87% and specificity of 85%. Metabolites including carnitine-C0, propionyl carnitine-C3 and phospholipid lysophosphatidylcholine acyl C14:0 have been reported to differentiate cows with metritis from healthy cows. Alterations in amino acids, myoinositol and urea have also been associated with retained placenta. Metabolomic changes have been reported in endometritis, metritis, retained placenta and repeat breeding, indicating their potential utility as predictive, diagnostic, prognostic and therapeutic biomarkers.

Microbiome and Metagenomics

The reproductive tract contains diverse microbial communities, and alterations in microbial composition have been associated with reproductive disease. Traditional microbiome studies have predominantly used 16S rDNA amplicon sequencing, whereas metagenomics provides a broader approach for characterising microbial communities. Amplicon sequencing provides information about specific taxonomic groups but may be influenced by primer-binding efficiency and differences in rDNA copy numbers. Metagenomics provides a more comprehensive analysis of mixed microbial communities and can include bacteria, viruses, fungi, parasites and other microorganisms. In contrast to 16S sequencing, metagenomic analysis can additionally provide information about functional genes present within the microbial community.

Approximately 30% of the reviewed studies investigated the reproductive tract microbiome. The most commonly investigated conditions were metritis and endometritis. Endometrial cytobrush samples, uterine swabs, uterine secretions and vaginal swabs were among the samples used for microbiome investigations. The major bacterial phyla identified in the bovine reproductive tract include Proteobacteria, Firmicutes, Bacteroidetes and Fusobacteria. Dysbiosis involving these

microbial groups has been associated with reproductive disorders. Endometritis has been associated with increased Fusobacteria and Bacteroidetes and reduced Proteobacteria, while metritis has been associated with increased Fusobacteria, Bacteroidetes and Firmicutes and decreased Proteobacteria. Specific bacterial groups have also been associated with particular reproductive disorders. Bacteroidetes pyogenes has been implicated in metritis, while Trueperella has been associated with endometritis. Histophilus and Mogibacteriaceae have also been associated with endometritis after calving. Porphyromonas and unidentified members of Pasteurellaceae have been associated with repeat breeding. These findings indicate that microbial composition and abundance may provide useful information for early detection and intervention in reproductive diseases.

Disease-Specific Biomarker Applications

Among the reproductive diseases investigated endometritis was the most frequently studied condition, accounting for 43% of the studies, followed by metritis at 30%. Other investigated conditions included uterine infections, metritis-endometritis combinations, retained placenta, salpingitis, vaginitis, cervicitis, repeat breeding, PVD and bovine genital campylobacteriosis. Endometritis has been investigated using inflammatory cytokines, acute-phase proteins, adipokines, transcriptomic markers, miRNAs, metabolites and microbiome characteristics. Metritis has been associated with inflammatory and metabolic biomarkers as well as alterations in the reproductive tract microbiome. Retained placenta has been associated with changes in cytokines, metabolites and acute-phase proteins. Reproductive diseases are characterised by interconnected changes in immune responses, metabolism, gene expression, protein expression and microbial communities. Consequently, the use of multiple biomarker classes may provide a more comprehensive representation of disease than assessment of an individual marker.

Treatment

Treatment of reproductive disorders in animals is increasingly shifting from individual treatment toward herd-level reproductive management. This approach combines pharmacological treatment with correction of management problems with greater emphasis on disease prevention and bio-security. Consumer concerns about antimicrobial and hormone residues and growing interest in organic and natural foods are also influencing treatment strategies. In small animals, treatment remains patient-focused but has become increasingly sophisticated.

Pharmacological Control

Reproductive hormones are widely used to suppress, induce, or synchronize reproductive activity.

- Progestogens: suppression or synchronization of estrus.
- Gonadotropins and GnRH: modification of gonadal function, including superovulation and induction of ovulation.

- PGF₂ α : termination of luteal function, estrus synchronization, treatment of pyometra, and induction of abortion in suitable species.
- Glucocorticoids, prostaglandins, and oxytocin: may be used to induce or manage parturition, with careful attention to timing and dosage.

Antimicrobial Treatment

Antimicrobials are used for reproductive tract infections in both males and females. Whenever possible, treatment should be guided by microbial culture and antimicrobial susceptibility testing. In food animals, meat and milk withdrawal periods must be followed, and drug selection during pregnancy requires caution because of possible fetal effects.

Surgical Treatment

Surgery is indicated for acquired reproductive tract abnormalities and injuries. Procedures include episiotomy, vestibulovaginal or cervical cerclage, cesarean section, and repair of preputial or penile injuries. Surgical sterilization, including gonadectomy and ovariectomy in appropriate species, is also routinely performed.

Overall, modern reproductive therapy combines hormonal manipulation, assisted reproduction, antimicrobial therapy, surgery, herd-level management, and preventive measures to improve reproductive efficiency while addressing concerns regarding fertility, drug residues, and animal health.

Current Knowledge Gaps

- Omics research remains limited in bulls despite their role as potential asymptomatic carriers of reproductive pathogens.
- Doppler and IRT provide complementary information on testicular perfusion, thermoregulation, spermatogenesis, and semen quality but their technical expert is not available in the field.
- Biomarkers require validation in larger populations and diverse conditions before clinical diagnostic application.

Future Directions

Future research should focus on clinically validating biomarkers for diagnostic and predictive applications. Integrating multi-omics approaches with other practical methods can provide comprehensive insights into reproductive disease mechanisms. Greater emphasis is needed on identifying biomarkers in bulls as it can act as a carrier of many infectious reproductive pathogens. Studying infected/carrier bulls alongside affected cows may improve understanding of herd-level infectious infertility and pathogen transmission.

Conclusion

Modern biomarker research is changing the approach to diagnosis and understanding of reproductive diseases in cattle. Overall integrated biomarker and multi-omics approaches have the potential to improve early detection, disease prediction, targeted treatment and reproductive

health management in cattle provided that candidate biomarkers are systematically validated before clinical implementation.

References

1. Juli, M.S.B., Boe-Hansen, G.B., Raza, A., Forutan, M., Ong, C.T., Siddle, H.V. and Tabor, A.E. (2024). A systematic review of predictive, diagnostic, and prognostic biomarkers for detecting reproductive diseases in cattle using traditional and omics approaches. *Journal of Reproductive Immunology*, 165, 104315.
2. Adnane, M. *et al.* (2017). Profiling inflammatory biomarkers in cervico-vaginal mucus postpartum: potential early indicators of bovine clinical endometritis? *Theriogenology*, 103, 117–122.
3. Almughlliq, F.B. *et al.* (2018). Proteomic content of circulating exosomes in dairy cows with or without uterine infection. *Theriogenology*, 114, 173–179.
4. Bicalho, M.L.S. *et al.* (2017). Genetic and functional analysis of the bovine uterine microbiota. Part II: Purulent vaginal discharge versus healthy cows. *Journal of Dairy Science*, 100, 3863–3874.
5. Bondurant, R.H. (2005). Venereal diseases of cattle: Natural history, diagnosis, and the role of vaccines in their control. *Veterinary Clinics of North America: Food Animal Practice*, 21, 383–408.
6. Brewer, A. *et al.* (2020). Qualitative and quantitative differences in endometrial inflammatory gene expression precede the development of bovine uterine disease. *Scientific Reports*, 10.
7. Chen, C. *et al.* (2022). Exosomal miR-218 regulates the development of endometritis in dairy cows by targeting TGIF2/TGF- β pathway. *Biocell*, 46.
8. Hailemariam, D. *et al.* (2014). [Metabolic biomarkers associated with periparturient reproductive disease].
9. Pereira, G. *et al.* (2020). Adipokines as biomarkers of postpartum subclinical endometritis in dairy cows. *Reproduction*, 160, 417–430.
10. Polo, C. *et al.* (2023). What about the bull? A systematic review about the role of males in bovine infectious infertility within cattle herds. *Veterinary and Animal Science*, 19, 100284.
11. Salilew-Wondim, D. *et al.* (2016). Clinical and subclinical endometritis induced alterations in bovine endometrial transcriptome and miRNome profile. *BMC Genomics*, 17.
12. Santos, T.M. and Bicalho, R.C. (2012). Diversity and succession of bacterial communities in the uterine fluid of postpartum metritic, endometritic and healthy dairy cows. *PLoS One*, 7, e53048.
13. Sheldon, I.M. *et al.* (2006). Defining postpartum uterine disease in cattle. *Theriogenology*, 65, 1516–1530.

FUTURE OF INTEGRATED AGRICULTURE–AQUACULTURE SYSTEMS: ZOOLOGICAL APPROACHES FOR SUSTAINABLE FOOD PRODUCTION

Dnyaneshwar Rameshwar Ingle

Department of Zoology,

Sir Parashurambhau College, Pune, Maharashtra, India

Corresponding author E-mail: dnyanu7046@gmail.com

Abstract

Integrated agriculture–aquaculture (IAA) represents a resource-efficient approach in which crop production, livestock, fisheries, aquaculture, microorganisms, and aquatic plants are functionally connected to improve nutrient utilization, diversify farm outputs, and reduce environmental losses. The basic principle is that wastes or by-products generated by one component can become inputs for another, thereby promoting nutrient recycling and circular food production. Historically, integrated fish–crop and fish–livestock systems have been particularly important in Asian smallholder agriculture, where ponds provide opportunities for nutrient recovery, water storage, food production, and livelihood diversification. Contemporary systems increasingly incorporate aquaponics, recirculating aquaculture systems, biofloc technology, integrated multitrophic aquaculture, microbial bioconversion, and renewable-energy technologies. Zoological principles are central to these systems because fish and other aquatic organisms act not only as food-producing organisms but also as biological components involved in nutrient transformation, trophic interactions, waste utilization, and ecosystem regulation. Integrated systems can improve resource-use efficiency when nutrient flows are appropriately balanced, although nutrient accumulation, disease transmission, energy requirements, technical complexity, and economic feasibility remain important considerations. Recent approaches emphasize measurable nutrient circularity, biodiversity, complementarity among species, and integration of biological and technological processes. Future IAA systems are therefore expected to combine zoology, aquaculture biotechnology, microbiology, agronomy, digital technologies, and ecological engineering to create resilient food-production systems capable of functioning under water scarcity, climate variability, land constraints, and increasing food demand.

Keywords: Integrated Agriculture–Aquaculture, Aquaculture, Zoology, Sustainable Agriculture, Fish Farming, Aquaponics, Nutrient Recycling, Circular Bioeconomy, Climate Resilience, Integrated Farming Systems.

1. Introduction

The increasing demand for food, freshwater, land and energy has created a need for agricultural systems that produce more food while minimizing resource consumption and environmental

impacts. Conventional crop and livestock production systems frequently operate as relatively independent enterprises, resulting in the loss of nutrients contained in animal manure, crop residues, wastewater and other biological wastes. Integrated agriculture–aquaculture (IAA) offers an alternative model in which different biological enterprises are connected through flows of water, nutrients, biomass and energy. The concept is well established in Asia, where fish ponds have traditionally been integrated with rice, vegetables, livestock and other agricultural activities to improve resource-use efficiency and diversify farm production [Prein, 2002]. Integrated agriculture–aquaculture systems can convert wastes from one enterprise into productive inputs for another, thereby improving resource utilization and environmental management [FAO/ICLARM/IIRR, 2001]. Modern IAA systems extend these principles through aquaponics, recirculating aquaculture systems, biofilters, microbial processing and precision technologies [Okomoda *et al.*, 2023]. Nutrient-flow studies have demonstrated that integrated systems can redirect nitrogen and phosphorus from aquaculture waste toward other biological components rather than allowing these nutrients to be discharged directly into the environment [Schneider *et al.*, 2005]. Integration of aquaculture with agricultural systems has also been investigated as a strategy for increasing production while reducing nutrient pollution [Farrant *et al.*, 2021]. Recent research has emphasized nutrient circularity, including productivity, recycling, self-sufficiency, regeneration, diversity and complementarity as important criteria for evaluating integrated aquaculture systems [Chary *et al.*, 2025]. Recirculating aquaculture systems provide additional opportunities for water conservation and nutrient management, although energy consumption and technical complexity remain important considerations [Martins *et al.*, 2010]. Sustainable aquaculture frameworks increasingly emphasize resource efficiency, environmental responsibility, resilience and climate-smart food production [FAO, 2025].

2. Concept and Biological Foundation of Integrated Agriculture–Aquaculture

Integrated agriculture–aquaculture is based on the deliberate connection of two or more farm enterprises so that materials generated in one component can support biological production in another. Typical combinations include rice–fish culture, vegetable–fish systems, livestock–fish farming, poultry–fish farming, duck–fish systems, pond-based horticulture, aquaponics and integrated multitrophic aquaculture [FAO/ICLARM/IIRR, 2001; Prein, 2002]. From a zoological perspective, fish and other aquatic organisms occupy important positions within these systems because they convert feed, plankton, detritus and other organic materials into animal biomass while simultaneously contributing to nutrient transformation [Schneider *et al.*, 2005]. The biological foundation therefore involves trophic relationships, decomposition, microbial transformation, nutrient uptake, grazing, predation and ecological succession. Future IAA systems should be designed according to measurable biological interactions and nutrient flows rather than simply placing enterprises together.

Table 1: Major components of integrated agriculture–aquaculture systems

Component	Biological Function	Potential Output
Fish	Conversion of feed and natural productivity into animal biomass	Fish protein
Crops	Uptake of nutrients and production of plant biomass	Grain, vegetables, fodder
Livestock	Production of manure and agricultural products	Meat, milk, eggs, manure
Aquatic plants	Nutrient uptake and water purification	Vegetable biomass, feed
Phytoplankton	Primary production and oxygen generation	Natural fish food
Zooplankton	Transfer of phytoplankton energy to fish	Live fish food
Bacteria	Decomposition and nutrient transformation	Mineral nutrients, microbial biomass
Biofilters	Nitrification and water purification	Reusable water
Detritivores	Conversion of organic residues into biomass	Additional food/feed

3. Rice–Fish and Crop–Fish Production Systems

Rice–fish farming is one of the most established forms of integrated agriculture–aquaculture and provides a strong example of how zoological processes can be incorporated into crop production [Prein, 2002]. Fish stocked in rice fields can consume insects, zooplankton, weeds and other aquatic organisms, while their movement can influence sediment processes and nutrient redistribution [FAO/ICLARM/IIRR, 2001]. In appropriate systems, nutrient cycling between sediment, water, microorganisms, plants and fish can reduce dependence on external inputs. Modern rice–fish systems can be enhanced through improved fish stocking strategies, water-level management, selective species combinations, biological pest regulation and real-time water-quality monitoring. Recent research has emphasized nutrient recycling and biological interactions within integrated rice–fish production systems [Chary *et al.*, 2025].

Table 2: Potential biological interactions in rice–fish systems

Interaction	Mechanism	Potential Benefit
Fish–insect	Fish consume aquatic insects/larvae	Biological pest regulation
Fish–plankton	Fish consume zooplankton	Energy transfer to fish biomass
Fish–sediment	Fish movement disturbs sediment	Nutrient redistribution
Rice–water	Plant roots absorb nutrients	Nutrient removal
Microbe–organic matter	Decomposition	Nutrient mineralization
Fish–rice habitat	Rice provides refuge	Improved biodiversity

4. Aquaponics: Integration of Fish and Plant Production

Aquaponics represents a technologically advanced form of agriculture–aquaculture in which recirculating aquaculture and hydroponic plant production are biologically connected. Fish excreta and uneaten feed contribute nitrogenous compounds and other nutrients to the water, while microorganisms convert toxic ammonia into less toxic forms that can subsequently be utilized by plants [Okomoda *et al.*, 2023]. Aquaponics therefore represents a combination of zoology, plant physiology, microbiology, engineering and water-quality management. Its potential advantages include reduced water consumption, simultaneous production of fish and vegetables, reduced nutrient discharge and efficient use of limited land resources. Successful operation requires appropriate balancing of fish biomass, feeding rate, plant biomass, microbial filtration, oxygen concentration, pH and nutrient availability [Okomoda *et al.*, 2023; Martins *et al.*, 2010].

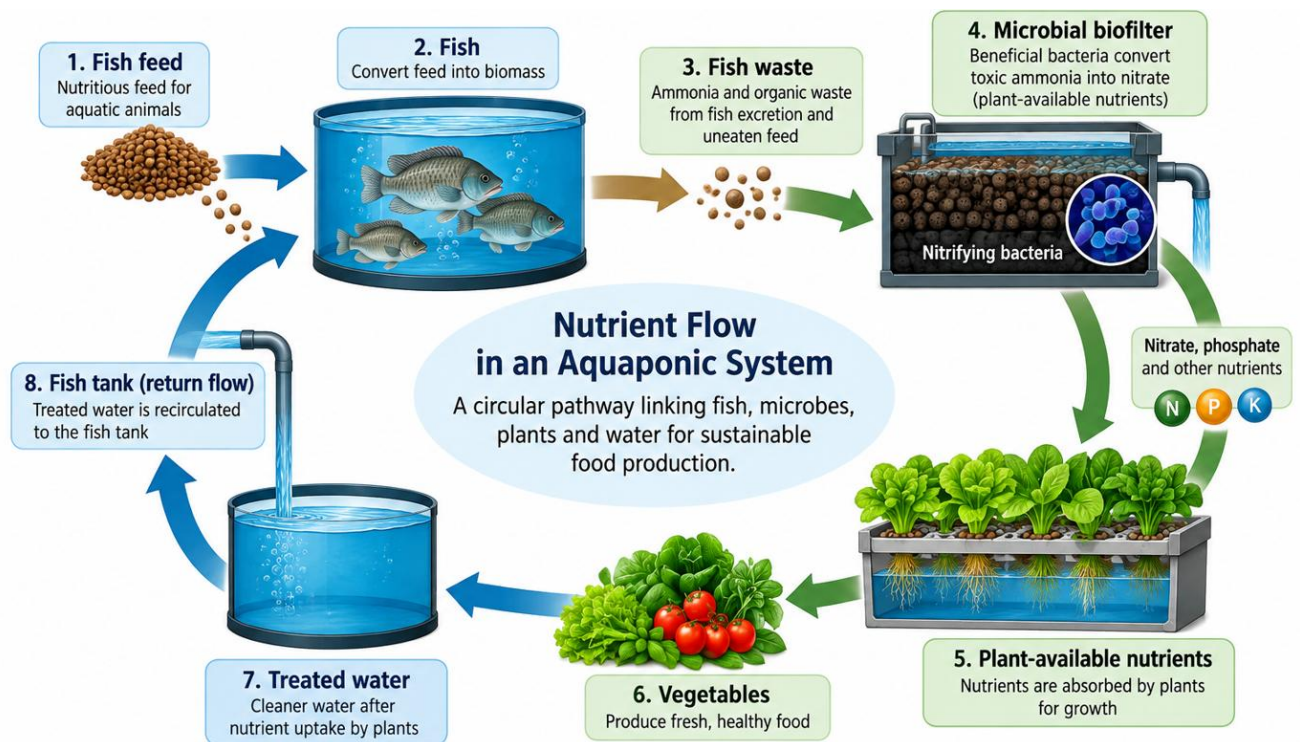


Figure 1: Conceptual nutrient flow in an aquaponic system showing the circular movement of nutrients from fish feed and fish production through fish waste, microbial biofiltration, plant nutrient uptake, vegetable production, water treatment, and recirculation to the fish tank. The pathway illustrates the biological integration of fish, microorganisms, plants, and water in sustainable agriculture–aquaculture systems

5. Livestock–Fish Integration and Circular Nutrient Management

Livestock–fish integration connects terrestrial animal production with aquatic food production through the recycling of organic resources [FAO/ICLARM/IIRR, 2001]. Poultry, ducks, pigs and cattle can contribute manure or other organic materials to properly designed pond systems, where

microbial decomposition and plankton production can contribute to fish nutrition [Prein, 2002]. However, direct transfer of untreated animal wastes into fish ponds may create risks related to excessive organic loading, oxygen depletion, pathogens, pharmaceutical residues and nutrient imbalance. Future livestock–fish systems should therefore employ controlled manure management, composting, anaerobic digestion, microbial treatment and appropriate biosecurity measures. The objective should be nutrient recovery rather than uncontrolled waste disposal.

6. Role of Microorganisms, Plankton and Detritivores

Microorganisms form the biological foundation of nutrient cycling in integrated agriculture–aquaculture systems. Heterotrophic bacteria decompose organic matter, nitrifying bacteria transform ammonia into nitrite and nitrate, and photosynthetic microorganisms contribute to primary production and oxygen dynamics [Schneider *et al.*, 2005]. Phytoplankton convert inorganic nutrients into biomass, while zooplankton transfer energy from primary producers to fish and other consumers. Benthic organisms and detritivores further contribute to the breakdown and recycling of organic residues. In integrated intensive aquaculture, nutrient-flow models have shown that biological components such as phototrophs, herbivores, bacteria and detritivores can influence the retention and transformation of nitrogen and phosphorus originating from feed [Schneider *et al.*, 2005].

Table 3: Biological agents and their functions

Biological Group	Principal Function	Application
Nitrifying bacteria	Ammonia → nitrite → nitrate	Biofilters
Heterotrophic bacteria	Organic matter decomposition	Biofloc
Phytoplankton	Primary production	Fish ponds
Zooplankton	Secondary production	Fish nutrition
Aquatic plants	Nutrient absorption	Aquaponics
Detritivores	Organic residue conversion	Integrated ponds
Microalgae	Nutrient recovery and biomass production	Wastewater treatment

7. Recirculating Aquaculture Systems and Water-Saving Agriculture

Recirculating aquaculture systems (RAS) are increasingly important for future integrated food production because they allow water to be treated and reused rather than continuously discharged [Martins *et al.*, 2010]. Mechanical filtration removes suspended solids, biological filtration facilitates nitrification, and additional treatment processes can control pathogens and dissolved contaminants. When RAS is connected with hydroponic plants, constructed wetlands, algae cultivation or other agricultural components, nutrients that would otherwise accumulate in the aquaculture loop can potentially be recovered as agricultural inputs [Okomoda *et al.*, 2023]. RAS can therefore form the technological core of intensive integrated agriculture–aquaculture systems, especially where water availability is limited. Nevertheless, energy consumption,

capital investment, technical expertise, equipment reliability and system complexity must be considered [Martins *et al.*, 2010].

Table 4: Conventional pond culture versus integrated recirculating systems

Parameter	Conventional Pond	Integrated/RAS-Based System
Water use	Relatively high	Potentially reduced
Nutrient recovery	Moderate	High potential
Production control	Moderate	High
Land productivity	Variable	Potentially high
Capital requirement	Lower	Higher
Technical requirement	Moderate	High
Waste recycling	Limited–moderate	Designed into system
Digital monitoring	Optional	Increasingly important

8. Zoological Approaches to Fish Health, Nutrition and Welfare

Fish health is a central requirement for integrated systems because high biological connectivity can increase both opportunities for nutrient recycling and risks associated with disease transmission. Zoological approaches include species selection, stocking density optimization, nutritional management, immunostimulation, probiotics, prebiotics, vaccination, parasite control, water-quality management and behavioral monitoring [FAO, 2025]. Fish should be selected according to environmental tolerance, feeding niche, growth rate and compatibility with other system components. Functional feeds containing probiotics, phytogenic compounds, algae, prebiotics and immunostimulatory ingredients may contribute to improved growth and physiological performance, although their effectiveness must be evaluated using controlled experimental studies. Maintaining appropriate dissolved oxygen, temperature, pH, ammonia, nitrite and stocking density is essential for animal welfare.

9. Precision Agriculture, Artificial Intelligence and Smart Aquaculture

The integration of digital technologies can transform conventional IAA into precision biological production systems. Sensors can continuously measure temperature, dissolved oxygen, pH, turbidity, electrical conductivity, ammonia and other environmental variables, while cameras can be used for fish behavior, feeding activity, biomass estimation and welfare assessment. Artificial intelligence and machine-learning algorithms can analyze these datasets to predict oxygen depletion, abnormal behavior, disease risk and feeding requirements. Automated feeders can optimize feeding according to fish biomass and activity, reducing feed wastage and nutrient discharge. Geographic information systems and remote sensing can also assist in selecting suitable sites and monitoring agricultural water resources [FAO, 2025].

Table 5: Emerging digital technologies

Technology	Zoological/Agricultural Application
IoT sensors	Water-quality monitoring
AI/ML	Disease and growth prediction
Computer vision	Fish behavior and biomass estimation
Automated feeders	Precision feeding
Drones	Farm and pond monitoring
GIS	Site and resource planning
Cloud platforms	Data storage and decision support
Digital twins	Simulation of integrated systems

10. Circular Bioeconomy, Climate Resilience and Future Prospects

The future of integrated agriculture–aquaculture lies in developing circular systems in which biological wastes are continuously transformed into useful products. Fish sludge, crop residues, livestock manure, aquatic weeds and food-processing wastes can potentially be converted into compost, biogas, biofertilizer, insect biomass, microbial protein or other value-added products after appropriate treatment. Integrated systems can also improve resilience by diversifying farm outputs; however, resilience should be evaluated according to water availability, energy requirements, climate exposure, disease risks, market conditions and socioeconomic feasibility. Recent research on nutrient circularity has proposed indicators based on productivity, efficiency, self-sufficiency, recycling, regeneration, diversity and complementarity [Chary *et al.*, 2025]. International sustainable-aquaculture guidance likewise emphasizes productive, efficient, resilient, climate-smart and environmentally responsible agrifood systems [FAO, 2025].

Table 6: Future research priorities for integrated agriculture–aquaculture

Research Area	Future Direction
Fish genetics	Climate-tolerant and disease-resistant strains
Microbiome	Beneficial microbial consortia
Nutrition	Low-cost functional and sustainable feeds
Waste management	Nutrient recovery and bioconversion
AI	Predictive farm management
Renewable energy	Solar-powered pumping and aeration
Climate adaptation	Heat- and drought-resilient systems
Biodiversity	Multi-species and trophic integration
Economics	Smallholder-oriented business models
Sustainability	Life-cycle and circularity assessment

Conclusion

Integrated agriculture–aquaculture represents a transition from linear food production toward interconnected biological production systems in which water, nutrients, biomass and energy are managed as interconnected resources. Zoology provides a fundamental scientific basis for these systems through the study of fish physiology, nutrition, behavior, reproduction, health, trophic interactions, biodiversity and aquatic ecosystem functioning. Traditional rice–fish and livestock–fish systems provide the foundation, while aquaponics, recirculating aquaculture, biofloc systems, microbial biotechnology and precision aquaculture provide pathways toward more technologically advanced production. The future of IAA should focus not simply on combining agricultural and aquaculture enterprises but on designing scientifically balanced biological networks in which nutrients are recovered, wastes are transformed, water is reused and multiple species contribute complementary functions. Digital technologies, artificial intelligence, molecular tools, probiotics, functional feeds, renewable energy and circular bioeconomy approaches can further improve system efficiency and resilience. At the same time, disease prevention, animal welfare, environmental safety, economic feasibility and farmer accessibility must remain integral to system design. A multidisciplinary framework combining zoology, fisheries science, microbiology, biotechnology, agronomy, environmental science and engineering can support the development of future-ready food-production systems capable of contributing to sustainable food security under increasing environmental and resource constraints.

References

1. Chary, K., Jaeger, C., Jansen, H. M., Harchaoui, S., & Aubin, J. (2025). Evaluating nutrient circularity in integrated aquaculture systems: Criteria and indicators. *Journal of Cleaner Production*, 504, 145414. <https://doi.org/10.1016/j.jclepro.2025.145414>
2. FAO/ICLARM/IIRR. (2001). *Integrated agriculture-aquaculture: A primer*. FAO Fisheries Technical Paper No. 407. Food and Agriculture Organization of the United Nations.
3. Food and Agriculture Organization of the United Nations. (2025). *Guidelines for sustainable aquaculture*. FAO. <https://doi.org/10.4060/cd3785en>
4. Farrant, D. N., Frank, K. L., & Larsen, A. E. (2021). Reuse and recycle: Integrating aquaculture and agricultural systems to increase production and reduce nutrient pollution. *Science of the Total Environment*, 785, 146859. <https://doi.org/10.1016/j.scitotenv.2021.146859>
5. Martins, C. I. M., Eding, E. H., Verdegem, M. C. J., Heinsbroek, L. T. N., Schneider, O., Blancheton, J. P., Roque d'Orbcastel, E., & Verreth, J. A. J. (2010). New developments in recirculating aquaculture systems in Europe: A perspective on environmental

- sustainability. *Aquacultural Engineering*, 43(3), 83–93.
<https://doi.org/10.1016/j.aquaeng.2010.09.002>
6. Okomoda, V. T., Oladimeji, S. A., Solomon, S. G., Olufeagba, S. O., Ogah, S. I., & Ikhwanuddin, M. (2023). Aquaponics production system: A review of historical perspective, opportunities, and challenges of its adoption. *Food Science & Nutrition*, 11(3), 1157–1165. <https://doi.org/10.1002/fsn3.3154>
 7. Prein, M. (2002). Integration of aquaculture into crop–animal systems in Asia. *Agricultural Systems*, 71(1–2), 127–146. [https://doi.org/10.1016/S0308-521X\(01\)00040-3](https://doi.org/10.1016/S0308-521X(01)00040-3)
 8. Schneider, O., Sereti, V., Eding, E. H., & Verreth, J. A. J. (2005). Analysis of nutrient flows in integrated intensive aquaculture systems. *Aquacultural Engineering*, 32(3–4), 379–401. <https://doi.org/10.1016/j.aquaeng.2004.09.001>
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FUTURE PERSPECTIVES OF HENNA (*LAWSONIA INERMIS* L.): AGRICULTURE BIOTECHNOLOGY AND MEDICINE

M. Kannahi* and R. Pragatha

PG and Research Department of Microbiology,
STET Women's College (Autonomous), Sundarakkottai 614016
(Affiliated to Bharathudasan University, Thiruchirappali)
Mannargudi, Thiruvavur, Tamil nadu, India

*Corresponding author E-mail: kannahiamf@gmail.com

Abstract

Henna (*Lawsonia inermis* L.), a member of the family Lythraceae, is an economically and medicinally important plant traditionally cultivated for its natural dye and therapeutic applications. The plant is particularly rich in lawsone, a naphthoquinone pigment responsible for its characteristic orange-red colour, along with flavonoids, phenolic compounds, terpenoids, tannins and other secondary metabolites. Increasing scientific interest in these phytochemicals has expanded the potential applications of henna beyond traditional cosmetic use. In agriculture, future research may focus on the development of high-lawsone cultivars, sustainable cultivation practices, climate-resilient production systems and utilization of marginal lands. Plant tissue culture, micropropagation, metabolic engineering and molecular approaches may further improve the production and conservation of elite henna varieties. In biotechnology, henna-derived compounds have potential applications in nanotechnology, antimicrobial materials, environmental remediation and value-added bioproduct development. In medicine, studies have reported antimicrobial, antioxidant, anti-inflammatory, wound-healing and potential anticancer properties associated with henna and its bioactive constituents. In particular, lawsone represents a promising natural scaffold for medicinal chemistry and drug-discovery research. However, differences in phytochemical composition, extraction methods, adulteration and limited clinical evidence remain important challenges. Future multidisciplinary research integrating agriculture, biotechnology, phytochemistry, nanotechnology and medicine may transform *L. inermis* into a sustainable source of natural dyes, bioactive compounds and pharmaceutical products. Standardization, toxicological evaluation and clinical validation will be essential for translating traditional knowledge into scientifically established applications.

Keywords: Lawsonia Inermis, Henna, Lawsone, Phytochemicals, Drug Discovery, Medicinal Plants, Value Added Byproduct Development, Natural Dye.

1. Introduction

Henna (*Lawsonia inermis* L.) is a flowering plant belonging to the family Lythraceae. It is widely recognized for its traditional use as a natural dye for skin, hair, textiles and other

materials. The characteristic colour of henna is mainly associated with lawsone (2-hydroxy-1,4-naphthoquinone), a naturally occurring naphthoquinone pigment present mainly in the leaves. In addition to lawsone, henna contains several classes of secondary metabolites, including flavonoids, phenolic compounds, tannins, terpenoids, steroids and other quinones. These phytochemicals are associated with several biological activities and have attracted increasing attention from pharmaceutical and biotechnology researchers (Mansour *et al.*, 2014; Singh *et al.*, 2015). Traditionally, henna has been used for cosmetic purposes and in various traditional medicinal practices. Modern research is now exploring its potential in antimicrobial formulations, antioxidant applications, wound management, drug discovery and nanotechnology. Therefore, the future importance of *L. inermis* may extend from traditional dye production to agriculture, biotechnology, medicine and environmental applications.

2. Phytochemical Basis of the Future Potential of Henna

The biological and industrial value of henna is closely associated with its diverse phytochemical composition. Lawsone is the most characteristic compound and is responsible for the staining properties of henna. Other phytochemicals include flavonoids, phenolics, tannins, terpenoids and coumarin-related compounds. These compounds may contribute to antioxidant, antimicrobial, anti-inflammatory and other biological activities reported for henna extracts. However, the concentration of bioactive compounds can vary according to geographical origin, soil conditions, climate, plant age, harvesting period and extraction method (Semwal *et al.*, 2014).

3. Future Perspectives in Agriculture

3.1 Development of High-Lawsone Varieties

One of the major agricultural objectives is the development of henna varieties with high and consistent lawsone content. Since lawsone contributes significantly to the commercial value of henna, selecting elite plants with desirable phytochemical profiles could improve natural dye production. Breeding programs combined with molecular characterization may help identify genotypes suitable for pharmaceutical and industrial applications.

3.2 Sustainable Henna Cultivation

Henna has potential for cultivation under relatively warm and dry environmental conditions. Future agricultural practices may focus on organic manures, biological fertilizers, efficient irrigation and integrated pest management. Sustainable cultivation could reduce the environmental impact of chemical inputs and improve the long-term productivity of henna plantations.

3.3 Climate-Resilient Cultivation

Climate change may influence crop productivity and secondary metabolite production. Therefore, future research should identify henna genotypes that can tolerate drought, heat and water stress.

Development of climate-resilient varieties may help maintain both biomass production and lawsone yield under changing environmental conditions.

3.4 Utilization of Marginal Lands

Henna may provide an opportunity for productive utilization of marginal or low-fertility lands. Cultivating henna in suitable non-prime agricultural areas could provide an additional source of income while reducing competition with major food crops. Further studies are required to determine suitable soil conditions, irrigation requirements and economically viable cultivation systems.

3.5 Precision Agriculture

Modern technologies such as remote sensing, GIS, drones and digital monitoring can potentially be applied to henna cultivation. These approaches may help monitor plant health, soil moisture, crop growth and harvesting conditions. Precision agriculture could therefore improve resource-use efficiency and support large- commercial cultivation.

4. Future Perspectives in Biotechnology

4.1 Plant Tissue Culture and Micropropagation

Plant tissue culture can provide an efficient method for rapid multiplication of selected *L. inermis* plants. Elite genotypes with high lawsone content, good growth and stress tolerance can potentially be multiplied under controlled conditions. Micropropagation may also contribute to the conservation of valuable genetic resources.

4.2 Secondary Metabolite Enhancement

Biotechnological approaches can be used to increase the production of valuable secondary metabolites. Elicitation, controlled culture conditions and cell-culture techniques may provide opportunities to enhance lawsone and other phytochemical production.

Understanding the biosynthetic pathway of lawsone will be particularly important for future metabolic engineering strategies (Nair *et al.*, 2024).

4.3 Molecular Biotechnology and Metabolic Engineering

Molecular studies can help identify genes and enzymes involved in lawsone biosynthesis. Once these pathways are better understood, metabolic engineering may be used to improve the production of commercially important compounds. Such approaches may eventually facilitate the development of henna plants with enhanced phytochemical characteristics.

4.5 Nanotechnology

Henna-derived phytochemicals have potential applications in green synthesis and nanobiotechnology. Plant-derived compounds may participate in the formation or stabilization of nanoparticles. Future research may explore henna-based nanomaterials for antimicrobial surfaces, biosensors, environmental applications and other functional materials (Kumar *et al.*, 2023).

4.5 Environmental Biotechnology

Henna biomass and its phytochemical constituents may have potential applications in environmental remediation. Future studies could investigate their ability to interact with dyes, heavy metals and other pollutants. The conversion of agricultural residues into useful environmental materials could contribute to a circular bioeconomy.

5. Future Perspectives in Medicine

5.1 Antimicrobial Applications

Henna extracts and lawsone have demonstrated antimicrobial activity against several microorganisms in experimental studies. This property provides an opportunity for the development of plant-based antimicrobial formulations (Singh *et al.*, 2015). Future research should focus on identifying the specific compounds responsible for antimicrobial activity and determining their mechanisms of action.

5.2 Antioxidant Potential

The presence of phenolic and flavonoid compounds contributes to the antioxidant potential of henna. Future research may investigate standardized henna extracts for potential applications in pharmaceutical and cosmetic formulations. Advanced analytical techniques can help determine which compounds contribute most strongly to antioxidant activity.

5.3 Anti-inflammatory Potential

Henna and its bioactive constituents have been investigated for anti-inflammatory activity. Lawsone and related compounds may influence biological pathways involved in inflammation (Nair *et al.*, 2024). Further experimental and clinical studies are required to determine whether these properties can be translated into safe therapeutic applications.

5.4 Wound-Healing Applications

Traditional use and experimental research have suggested potential wound-healing properties of *L. inermis*. Future studies could focus on developing standardized topical formulations such as creams, gels or ointments. However, appropriate toxicological and clinical evaluation is essential before therapeutic recommendations can be established.

5.5 Anticancer Research

Lawsone and related naphthoquinones have attracted interest in cancer research. Experimental studies suggest that these compounds may influence cellular processes associated with proliferation and programmed cell death.

Recent research has also explored chemically modified lawsone derivatives as potential candidates for medicinal chemistry and drug-discovery applications (Nair *et al.*, 2024).

These findings are mainly experimental, and further *in vivo* and clinical investigations are necessary.

5.6 Drug Discovery

Lawsone represents a promising natural-product scaffold for the development of new bioactive molecules. Structural modification of lawsone may produce derivatives with improved biological activity or pharmacological properties.

Future medicinal chemistry research could therefore focus on designing, synthesizing and evaluating novel lawsone derivatives (Nair *et al.*, 2024).

6. Standardization and Quality Control

One of the major challenges in developing medicinal products from henna is the variation in phytochemical composition. Factors such as geographical origin, cultivation conditions, harvesting stage, processing and storage can influence the concentration of active compounds.

Therefore, future research should establish standardized extraction procedures, chemical fingerprints and marker-compound-based quality-control methods.

Analytical techniques such as HPLC, LC-MS, GC-MS, FTIR and metabolomics can support authentication, quality assessment and detection of adulteration.

7. Safety and Toxicological Perspectives

Although henna has a long history of traditional use, future pharmaceutical applications require systematic safety evaluation. Research should include acute and chronic toxicity studies, pharmacokinetic investigations, dose optimization and controlled clinical trials.

Special attention should be given to distinguishing pure henna from adulterated products containing additional chemical ingredients. Establishing standardized and well-characterized preparations will be essential for safe medicinal development (Mansour *et al.*, 2012).

8. Future Research Directions

Future research on *Lawsonia inermis* should concentrate on:

- Development of high-lawsone cultivars
- Climate-resilient and sustainable cultivation
- Plant tissue culture and micropropagation
- Molecular characterization of lawsone biosynthesis
- Metabolic engineering
- Green synthesis of nanomaterials
- Environmental remediation
- Isolation of novel bioactive compounds
- Development of standardized pharmaceutical formulations
- Lawsone-based drug discovery
- Toxicological and pharmacokinetic studies
- In vivo and clinical validation

Conclusion

Lawsonia inermis L. has considerable potential as a multifunctional plant extending beyond its traditional role as a natural dye. Its phytochemical diversity, particularly the presence of lawsone, provides opportunities for research in agriculture, biotechnology, medicine, nanotechnology and environmental biotechnology.

Future developments in molecular biology, plant biotechnology, metabolic engineering, precision agriculture and medicinal chemistry may improve the production and utilization of valuable henna-derived compounds. At the same time, standardization, safety evaluation and clinical validation are essential to establish scientifically reliable applications.

Thus, multidisciplinary research combining agriculture, biotechnology, phytochemistry, nanotechnology and medicine may transform henna into a valuable source of sustainable natural products and future bio-based technologies.

References

1. Mansour, D., Kahlouche, A., & Trifa, W. (2012). In vitro evaluation of anti-fungal effect of *Lawsonia inermis*, *Pistacia lentiscus* and *Juglans regia*. *International Journal of Aromatic and Medicinal Plants*, 2(2).
2. Singh, P., Luqman, S., & Marthur, A. K. (2015). *Lawsonia inermis*—A commercially important primaeval dyeing and medicinal plant with diverse pharmacological activity: A review. *Industrial Crops and Products*, 65, 269–286.
3. Nair, A. S., Sekar, M., Gan, S. H., Kumarasamy, V., Subramaniyan, V., Wu, Y. S., Mat Rani, N. N. I., Ravi, S., & Wong, L. S. (2024). Lawsone unleashed: A comprehensive review on chemistry, biosynthesis and therapeutic potential. *Drug Design, Development and Therapy*, 18, 3295–3313.
4. Semwal, R. B., Semwal, D. K., Combrinck, S., Cartwright-Jones, C., & Viljoien, A. (2014). *Lawsonia inermis* L. (henna): Ethnobotanical, phytochemical and pharmacological aspects. *Journal of Ethnopharmacology*, 155(1), 80–103.

A REVIEW ON IOT BASED SMART FARMING SYSTEM

Subhrajit Ray

Department of Mechanical and Electrical Engineering, CAET,
Odisha University of Agriculture and Technology, Odisha-751003

Corresponding author E-mail: sray.mee@ouat.ac.in

Abstract

Agriculture is one of the oldest occupations and provides food for people all over the world. Many changes are taking place in agriculture to increase crop production. Researchers are using different technologies to improve farming methods. One important technology used in farming is the Internet of Things (IoT), which helps farmers monitor plants and fields from distant locations. This modern method is called smart farming. Smart farming allows farmers to observe their fields and manage farming activities remotely. It reduces the need for manual labor and improves the efficient use of resources such as water and electricity. This article studies the architecture of smart farming and explains different smart farming techniques. These techniques are divided into three main categories: IoT-based agricultural monitoring and control systems, automatic irrigation systems, and plant disease monitoring systems. The review is based on the systematic literature review method, and the critical findings of the research articles were analyzed. The study also reviews different IoT technologies such as sensors, gateways, communication systems, user interfaces, experiment types, plant types, disease types, along with their advantages and limitations. Finally, the article discusses future research directions and challenges related to smart farming technologies.

1. Introduction

The world population is expected to reach 9.7 billion by 2050, increasing the demand for food [1]. To improve crop production and reduce human effort, technologies like sensors [2], GPS [3], and remote sensing [4] are used in agriculture. However, these systems have limitations such as high cost, complex structure, and lack of remote access. To overcome these problems, the Internet of Things (IoT) is introduced in farming. IoT connects different devices and allows farmers to monitor and control agricultural activities remotely [5]. It also improves efficiency and reduces manpower. In Agricultural IoT (AIoT), sensors and actuators are used to monitor environmental conditions and support activities such as plant monitoring, automatic irrigation, pest control, and food storage [6]. This article reviews IoT applications in agriculture using a systematic literature review method. The study mainly focuses on three areas: agricultural monitoring and control systems, automatic irrigation systems, and plant disease detection systems.

2. Smart Farming

Smart farming is the use of advanced technologies in agriculture to reduce waste and increase productivity. It uses modern tools to support different farming activities such as crop monitoring, soil management, irrigation, pest control, and product delivery tracking [7]. Smart farming technologies include sensors for temperature, light, humidity, pressure, and soil chemicals, along with drones, cameras, GPS, communication networks, and agricultural management systems [8]. The use of technology in agriculture is becoming increasingly important. The precision agriculture market is expected to generate about US\$10 billion in revenue by 2023[9]. Smart farming also helps improve food production by using water in irrigation, fertilizers, and pesticides more efficiently [10].

3. IoT in Farming

This section explains the role of Internet of Things (IoT) technologies in agriculture. Agricultural production depends on several factors such as crop type, water availability, temperature, soil condition, soil nutrients, and sunlight. To measure these factors, low-cost and lightweight sensors are used in farms. These sensors collect environmental data, but many cannot directly connect to the Internet.

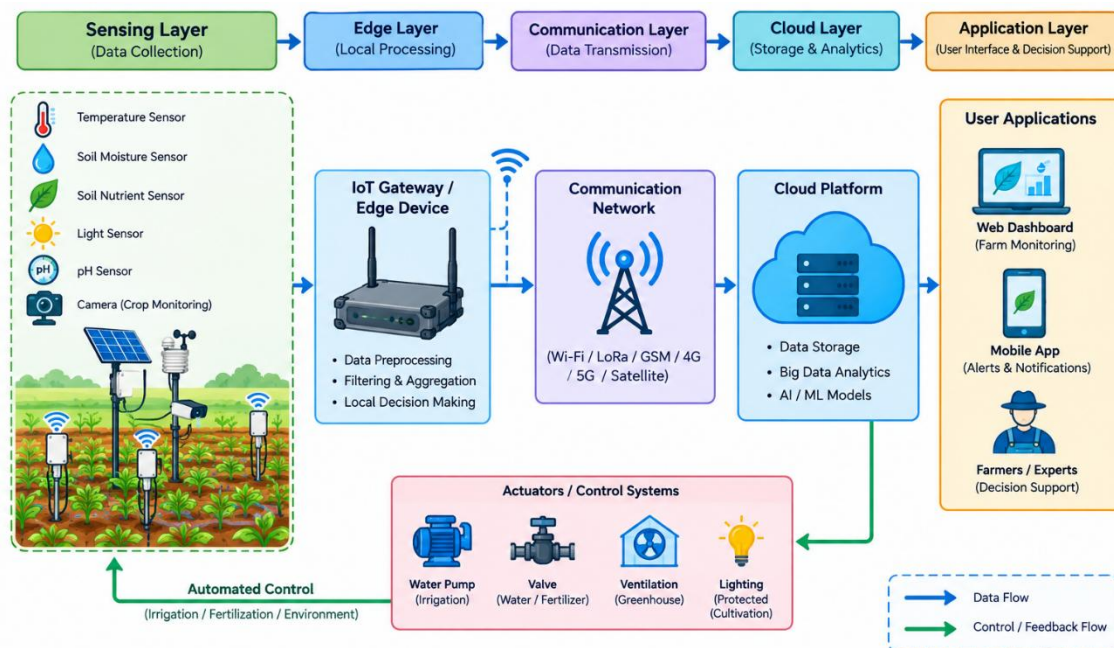


Figure 1: Overall architecture of IoT-based smart farming

Therefore, gateway devices are used to gather data from sensors, process the raw information, and send it to the Internet. Communication between sensors and gateways is established using protocols such as ZigBee and message queuing telemetry transport (MQTT), which are suitable for low-cost devices. Gateways use Wi-Fi or GPRS to transfer data to cloud platforms or databases like MySQL and NoSQL. The stored data are analyzed using machine learning and big data techniques for better decision-making. IoT systems also allow farmers to remotely control

devices such as water pumps and fog pumps. In addition, many farming activities can be automated. For example, irrigation systems can automatically start when soil moisture becomes low, and artificial lights can turn on when sunlight is insufficient. These automated systems reduce human effort and improve agricultural productivity. IoT technology is useful not only in traditional farming but also in hydroponic farming, where plants grow in nutrient solutions instead of soil. IoT helps monitor and control nutrient levels effectively, ensuring healthy plant growth. Overall architecture of IoT-based smart farming is shown in figure 1.

4. Smart Agriculture Automation Using Internet of Things (IoT)

IoT-based agricultural monitoring systems use various sensors, communication technologies, and cloud platforms to observe environmental conditions and automate farming activities remotely. Farmers can monitor parameters such as temperature, humidity, soil moisture, pH, light intensity, and water quality through web portals or mobile applications. Several studies have demonstrated that IoT technologies improve crop productivity, resource utilization, and decision-making efficiency. Ma *et al.* developed a water quality monitoring system for farm ponds using sensors to measure pH, dissolved oxygen, temperature, and water level, while data were transmitted through IEEE 802.15.4 and GPRS communication technologies. The system enabled remote monitoring and automatic control of farm equipment using SMS services [12]. Liu proposed an IoT-based farmland monitoring system using ZigBee communication and multiple environmental sensors, including CO₂, temperature, humidity, and soil moisture sensors [13]. In greenhouse applications, Lamprinos and Charalambides analyzed ZigBee communication performance using environmental sensors and demonstrated the importance of proper sensor placement for reliable communication [14]. Palande *et al.* designed an automated hydroponic system that controlled pH, temperature, CO₂ concentration, and artificial lighting using Arduino and Raspberry Pi platforms [15]. Similarly, Yung *et al.* integrated cloud computing and Hadoop-based big data analysis with IoT greenhouse monitoring systems to improve data analysis and decision-making [16]. Precision agriculture and automation techniques have also been widely explored. Ferrández-Pastor *et al.* implemented fog computing and machine learning techniques for irrigation and plant growth optimization [17]. Zhang *et al.* proposed an IoT-based citrus orchard monitoring system integrated with decision-making and Web GIS technologies for efficient irrigation and fertilization management [18]. Recent studies have focused on energy-efficient and intelligent agricultural systems. Maia *et al.* developed a portable solar-powered IoT monitoring device using ZigBee communication and Raspberry Pi for environmental monitoring [19]. Geng and Dong combined IoT with deep learning techniques for intelligent plant monitoring and automated decision-making [20]. Additionally, LoRa-based agricultural monitoring systems were investigated for low-power communication in large farm areas [21]. Overall, IoT-based agricultural monitoring systems provide real-time monitoring, remote

accessibility, automation, and improved agricultural productivity. However, challenges such as security, power consumption, scalability, and implementation cost still require further research and development. Data flow architecture with IoT communication is presented in figure 2.

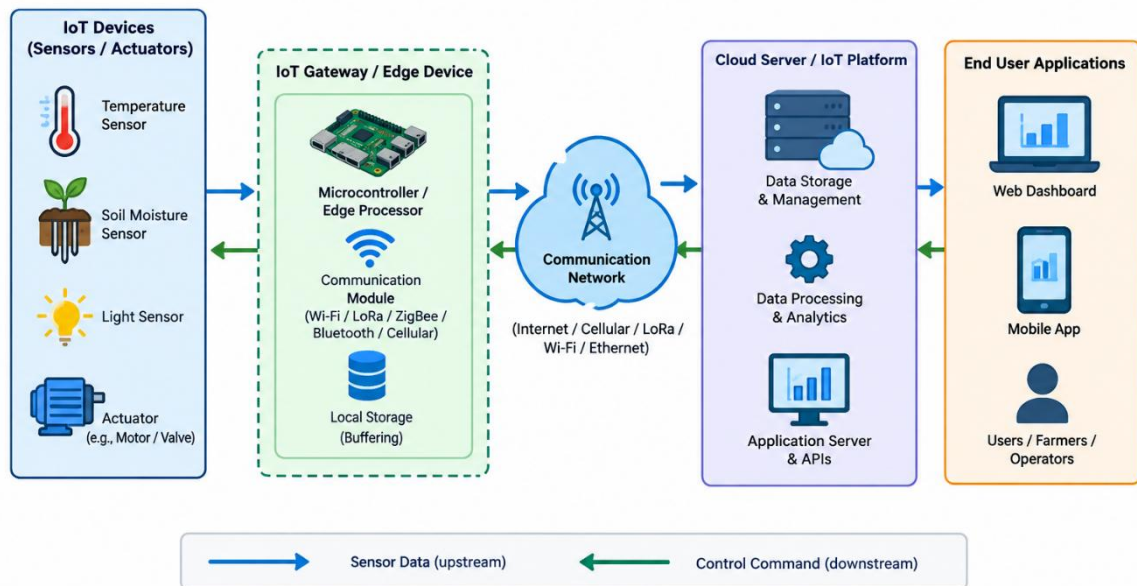


Figure 2: IoT communication and data-flow architecture

5. Smart Agriculture Irrigation System Using IoT

In IoT-based automatic irrigation systems, irrigation is controlled automatically according to environmental conditions, reducing water wastage and minimizing farmers' effort. Various smart irrigation approaches have been proposed in recent years. Subashini *et al.* developed a smart farming system using sensors for soil moisture, temperature, humidity, and light intensity [22]. Data were transmitted through an AVR microcontroller and Wi-Fi module to the ThingSpeak cloud platform. The irrigation pump operated automatically based on environmental conditions. However, the prototype was tested only for three days and lacked detailed performance analysis. Mohanraj *et al.* proposed an agricultural monitoring system using Arduino Uno and TI CC3200. Soil moisture, light intensity, and weather forecast data were used for irrigation planning. The system also provided SMS alerts to farmers regarding irrigation and fertilizer application, though statistical analysis was not provided [23]. Sureephong *et al.* designed a smart wetting front detector using resistor-based and FDR soil sensors. The system transmitted soil moisture and temperature data via Wi-Fi, where the FDR sensor showed better precision [24]. The portable prototype was tested for 30 days. Goap *et al.* developed an IoT irrigation system integrated with machine learning and weather prediction. Sensors collected field data, which were processed using Raspberry Pi and Arduino through ZigBee and Wi-Fi communication [25]. The system predicted rainfall and optimized irrigation, although the system cost was high. Keswani *et al.* proposed a solar-powered smart irrigation system using ZigBee and fuzzy logic for weather prediction. Structural similarity techniques were applied to identify dry regions, enabling

selective sprinkler operation and water conservation [26]. Agale *et al.* designed a small-scale prototype using Raspberry Pi and sensor nodes for automated irrigation and web-based monitoring. However, detailed experimental and statistical results were not discussed [27]. Salvi *et al.* introduced an indoor IoT irrigation system using moisture, temperature, humidity, and light sensors connected through Bluetooth and ThingSpeak cloud storage. The system automatically controlled irrigation, though efficiency metrics were missing [28]. Shekhar *et al.* applied the K-nearest neighbor (KNN) machine learning algorithm for smart irrigation. Environmental data were processed using Raspberry Pi, and irrigation decisions were made automatically. Experimental results were explained clearly but were limited to small-scale implementation [29]. Imteaj *et al.* proposed a GSM-based irrigation system using soil moisture, water level, and light sensors. The system automatically operated water pumps and informed users through SMS. However, the prototype was tested only in a small area [30]. Monica *et al.* designed a smart irrigation system using GSM, Wi-Fi, and Bluetooth communication. Experimental results on groundnut plants showed reduced water consumption, but improvements in energy efficiency and weather prediction were suggested [31].

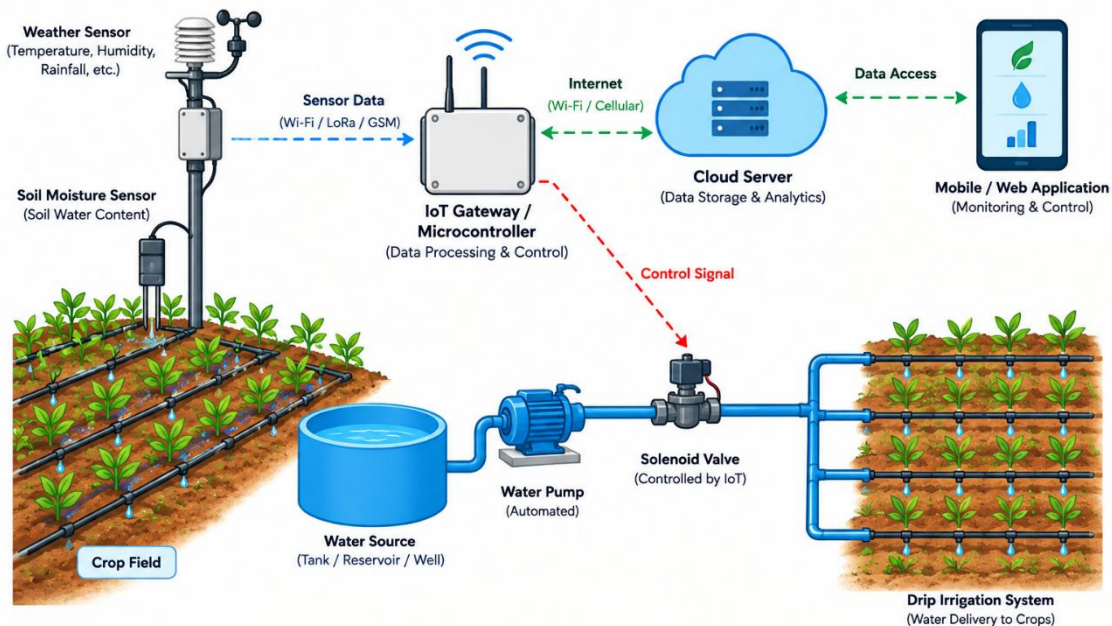


Figure 3: IoT-based smart irrigation system

Rajalakshmi and Mahalakshmi automated irrigation using soil moisture, temperature, humidity, light, and ultrasonic sensors. Data were transmitted through ZigBee and Wi-Fi to cloud storage, allowing remote motor control [32]. The study reported reduced water usage after two months of testing. Vaishali *et al.* developed a mobile application-based irrigation system using Raspberry Pi and Bluetooth communication. The system monitored moisture and temperature conditions and controlled irrigation automatically, though detailed experimental results were unavailable [33]. Kumar *et al.* proposed a scalable IoT irrigation system using soil moisture, rain, water flow, and

temperature sensors. Raspberry Pi controlled irrigation and cloud-based monitoring, enabling precise water distribution and flow control [34]. A model of Smart Agriculture Irrigation System Using IoT is shown in figure 3.

6. Plant Disease Monitoring Using IoT

Potamitis *et al.* proposed smart insect traps that monitored pests remotely using light emitters and receivers. Insect movement interrupted the light signal, enabling insect counting. Data were transmitted through GPRS using TCP/IP and HTTP protocols. Although the system achieved high accuracy and scalability, environmental factors such as rain affected the results [35]. Rustia and Lin developed a greenhouse insect monitoring system using Raspberry Pi, cameras, and environmental sensors. Images and environmental data were transmitted through Wi-Fi or 4G networks and stored in an SQL database. The system successfully detected insect pests, though experiments were conducted for limited duration and plant samples [36]. Thorat *et al.* designed an IoT-based plant disease detection system using soil moisture, temperature, humidity sensors, and cameras. Plant images were processed using OpenCV to identify diseases such as black spot, rust, and powdery mildew. The system produced encouraging results but lacked scalability for large agricultural fields [37]. Kapoor *et al.* integrated image processing with IoT to monitor environmental conditions and detect factors affecting plant growth. Sensors and cameras collected data, which were analyzed using MATLAB. The study considered environmental factors along with disease analysis, but the system was not fully automated or scalable [38]. Rau *et al.* proposed a smart irrigation and nutrient deficiency detection system for rice plants. Raspberry Pi and image processing techniques compared leaf color with the International Rice Color Chart (IRCC) to identify nitrogen deficiency and diseases such as bacterial blight [39]. However, the system required high-resolution cameras and lacked full automation. Pérez-Expósito *et al.* developed VineSens, an IoT-based vineyard monitoring system for detecting downy mildew disease. Temperature, humidity, and soil sensors were connected through ESP8266 and Raspberry Pi gateways. The system predicted disease occurrence using the Rule 3-10 model and recommended phytosanitary treatments. The system achieved high scalability and accuracy [40]. Kim *et al.* proposed a disease prediction system for strawberry plants using LoRa-based IoT devices. Sensors monitored greenhouse conditions such as temperature, humidity, and CO₂ concentration to predict *Botrytis cinerea* disease and recommend nutrient solutions [41]. Overall, IoT-based disease and pest detection systems help farmers protect crops from diseases and insects. However, many systems lack detailed accuracy analysis, energy-efficient operation, and scalability for large agricultural fields. Camera-based disease detection may be difficult for large farms; therefore, drone-based monitoring and environmental-condition-based disease prediction can provide better large-scale solutions. Plant disease and pest monitoring using IoT is presented in figure 4.

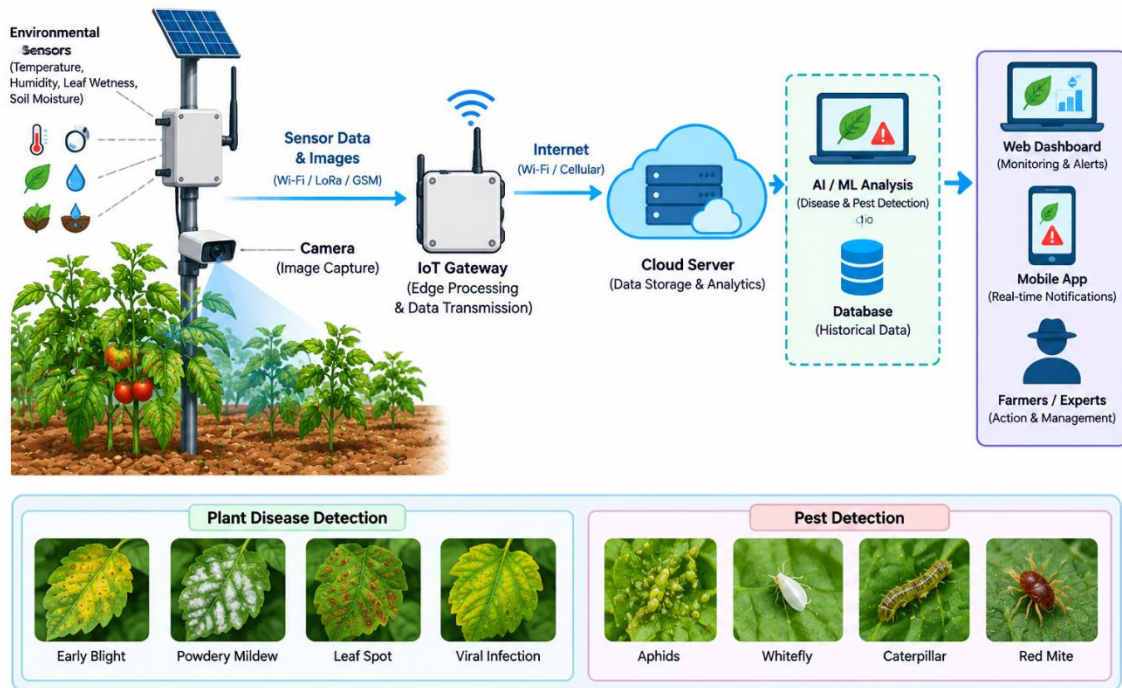


Figure 4: IoT-based plant disease and pest monitoring

7. Discussion

The evolution of IoT in agriculture has significantly improved farming practices; however, several challenges still need to be addressed for future smart agricultural systems.

Security: Most IoT communication protocols are vulnerable to cyberattacks. Technologies such as ZigBee and IEEE 802.11 face issues including data manipulation, traffic sniffing, jamming, and passive attacks. Therefore, secure communication and trust management mechanisms are essential for reliable agricultural IoT systems [42].

Renewable Energy Usage: Only a few existing smart farming systems utilize renewable energy sources. Future IoT systems should adopt solar, thermoelectric, electromagnetic, and radio-frequency energy harvesting methods to reduce dependence on batteries and electrical power.

Scalability: Agricultural activities are generally performed over large areas. Although many IoT systems are scalable, large-scale deployment introduces challenges related to cost, data storage, synchronization, reliability, and aggregation [43].

Cost: High-quality IoT sensors and devices are still expensive, creating financial burdens for farmers. Developing low-cost and accurate IoT devices is necessary for widespread adoption.

Connectivity and Supply Chain: IoT technologies should improve communication between farmers, distributors, and customers to better understand market demand and crop requirements. Although some research has been conducted in IoT-based food supply management, real-time implementation challenges still remain [44].

Compatibility with Advanced Technologies: Future IoT systems should integrate with technologies such as big data analytics, machine learning, resource allocation, and service

composition techniques to efficiently process large volumes of agricultural data and improve automation [45].

Early Prediction and Decision Support: Climate change and global warming significantly affect agriculture. IoT systems should support early prediction of rainfall, droughts, and cyclones, while also recommending suitable crops according to future climatic conditions.

Pilot IoT agricultural projects in China and Europe have highlighted several large-scale implementation challenges. Integration of IoT with satellite remote sensing technologies can further improve large-scale monitoring of soil and environmental conditions in agriculture [46].

Future challenges are presented in a flowchart in figure 5.

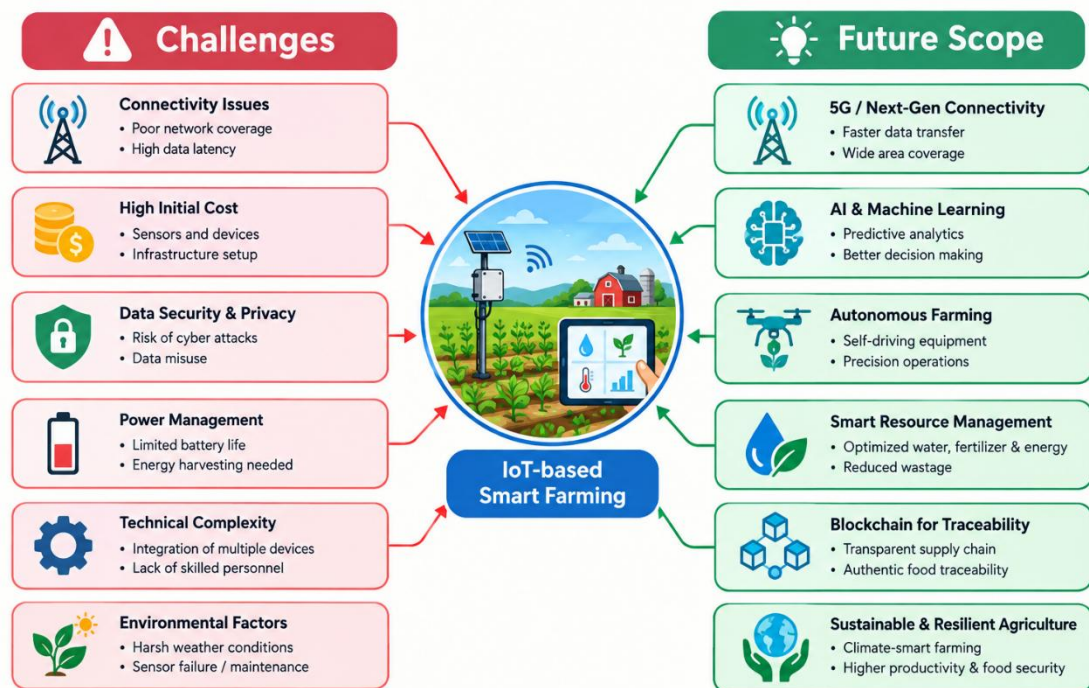


Figure 5: Challenges and future scope of IoT-based smart farming

Conclusion

Agriculture plays a vital role in society, and the integration of IoT technologies has significantly improved modern farming practices. IoT applications are widely used in areas such as farm monitoring, smart irrigation, pest detection, and crop management. From the review of existing smart farming systems, it is observed that researchers need to focus more on security, food supply management, and food distribution systems. Additionally, most current studies and experiments have been conducted in indoor environments. To address real-world agricultural challenges more effectively, future research should emphasize outdoor and large-scale implementations. Overall, this study provides a clear understanding of the current status and future scope of IoT-based smart agriculture systems.

References

1. Elijah, O., Rahman, T. A., Orikumhi, I., Leow, C. Y., & Hindia, M. H. D. N. (2018). An overview of internet of things (IoT) and data analytics in agriculture: Benefits and challenges. *IEEE Internet of Things Journal*, 5(5), 3758–3773.
2. Fukatsu, T., Kiura, T., & Hirafuji, M. (2011). A web-based sensor network system with distributed data processing approach via web application. *Computer Standards & Interfaces*, 33(6), 565–573.
3. Zheng, L., Li, M., Wu, C., *et al.* (2011). Development of a smart mobile farming service system. *Mathematical and Computer Modelling*, 54(3–4), 1194–1203.
4. Kim, Y., Evans, R. G., & Iversen, W. M. (2008). Remote sensing and control of an irrigation system using a distributed wireless sensor network. *IEEE Transactions on Instrumentation and Measurement*, 57(7), 1379–1387.
5. Sangeetha, A. L., Bharathi, N., Ganesh, A. B., & Radhakrishnan, T. K. (2018). Particle swarm optimization tuned cascade control system in an Internet of Things (IoT) environment. *Measurement*, 117, 80–89.
6. Hafidh, B., Al Osman, H., Arteaga-Falconi, J. S., Dong, H., & Saddik, A. E. (2017). SITE: The simple Internet of Things enabler for smart homes. *IEEE Access*, 5, 2034–2049.
7. Bhagat, M., Kumar, D., & Kumar, D. (2019). Role of Internet of Things (IoT) in smart farming: A brief survey. In *Proceedings of the IEEE 2019 Devices for Integrated Circuit (DevIC)*, Kalyani, India, 23–24 March 2019 (pp. 141–145).
8. Stořces, M., Vanřek, J., Masner, J., & Pavlík, J. (2016). Internet of Things (IoT) in agriculture—Selected aspects. *Agris on-line Papers in Economics and Informatics*, VIII, 83–88.
9. Statista. (n.d.). *Forecasted market value of precision farming worldwide in 2018 and 2023*. <https://www.statista.com/statistics/721921/forecasted-market-value-of-precision-farming-worldwide/>
10. Kite-Powell, J. (2018). *Why precision agriculture will change how food is produced*. Forbes. <https://www.forbes.com/sites/jenniferhicks/2018/04/30/why-precision-agriculture-will-change-how-food-is-produced/#1aa438ec6c65>
11. Terence, S., & Purushothaman, G. (2020). Systematic review of Internet of Things in smart farming. *Transactions on Emerging Telecommunications Technologies*, 31(6), e3958.
12. Ma, D., Ding, Q., Li, Z., Li, D., & Wei, Y. (2012). Prototype of an aquacultural information system based on Internet of Things E-nose. *Intelligent Automation & Soft Computing*, 18(5), 569–579.
13. Liu, J. (2016). Design and implementation of an intelligent environmental-control system: Perception, network, and application with fused data collected from multiple sensors in a

- greenhouse at Jiangsu, China. *International Journal of Distributed Sensor Networks*, 12(7), 5056460.
14. Lamprinos, I., & Charalambides, M. (2015). Experimental assessment of ZigBee as the communication technology of a wireless sensor network for greenhouse monitoring. *International Journal of Advanced Smart Sensor Network Systems*, 6, 1–10.
 15. Palande, V., Zaheer, A., & George, K. (2018). Fully automated hydroponic system for indoor plant growth. *Procedia Computer Science*, 129, 482–488.
 16. Yang, J., Liu, M., Lu, J., Miao, Y., Hossain, M. A., & Alhamid, M. F. (2018). Botanical Internet of Things: Toward smart indoor farming by connecting people, plant, data and clouds. *Mobile Networks and Applications*, 23(2), 188–202.
 17. Ferrández-Pastor, F. J., García-Chamizo, J. M., Nieto-Hidalgo, M., & Mora-Martínez, J. (2018). Precision agriculture design method using a distributed computing architecture on Internet of Things context. *Sensors*, 18(6), 1731.
 18. Zhang, X., Zhang, J., Li, L., Zhang, Y., & Yang, G. (2017). Monitoring citrus soil moisture and nutrients using an IoT based system. *Sensors*, 17(3), 447.
 19. Maia, R. F., Netto, I., & Ho-Tran, A. L. (2017). Precision agriculture using remote monitoring systems in Brazil. In *Proceedings of the 2017 IEEE Global Humanitarian Technology Conference (GHTC)* (pp. 1–6). IEEE.
 20. Asghari, P., Rahmani, A. M., & Javadi, H. H. S. (2019). Internet of Things applications: A systematic review. *Computer Networks*, 148, 241–261.
 21. Jatoth, C., Gangadharan, G. R., & Buyya, R. (2015). Computational intelligence based QoS-aware web service composition: A systematic literature review. *IEEE Transactions on Services Computing*, 10(3), 475–492.
 22. Subashini, M., Das, S., Heble, S., Raj, U., & Karthik, R. (2018). Internet of Things based wireless plant sensor for smart farming. *Indonesian Journal of Electrical Engineering and Computer Science*, 10(2), 456–468.
 23. Mohanraj, I., Ashokumar, K., & Naren, J. (2016). Field monitoring and automation using IoT in agriculture domain. *Procedia Computer Science*, 93, 931–939.
 24. Sureephong, P., Wiangnak, P., & Wicha, S. (2017). The comparison of soil sensors for integrated creation of IoT-based wetting front detector (WFD) with an efficient irrigation system to support precision farming. In *Proceedings of the International Conference on Digital Arts, Media and Technology (ICDAMT)* (pp. 132–135). IEEE.
 25. Goap, A., Sharma, D., Shukla, A. K., & Krishna, C. R. (2018). An IoT based smart irrigation management system using machine learning and open source technologies. *Computers and Electronics in Agriculture*, 155, 41–49.

26. Keswani, B., Mohapatra, A. G., Mohanty, A., *et al.* (2018). Adapting weather conditions based IoT enabled smart irrigation technique in precision agriculture mechanisms. *Neural Computing and Applications*, 31(1), 1–16.
27. Agale, R., & Gaikwad, D. P. (2017). Automated irrigation and crop security system in agriculture using Internet of Things. In *Proceedings of the 2017 International Conference on Computing, Communication, Control and Automation (ICCUBE)* (pp. 1–5). IEEE.
28. Salvi, S., Jain, S. A. P., Sanjay, H. A., Harshita, T. K., Farhana, M., Jain, N., & Suhas, M. V. (2017). Cloud based data analysis and monitoring of smart multi-level irrigation system using IoT. In *Proceedings of the 2017 International Conference on I-SMAC (IoT in Social, Mobile, Analytics and Cloud) (I-SMAC)* (pp. 752–757).
29. Shekhar, Y., Dagur, E., Mishra, S., & Sankaranarayanan, S. (2017). Intelligent IoT based automated irrigation system. *International Journal of Applied Engineering Research*, 12(18), 7306–7320.
30. Imteaj, A., Rahman, T., Hossain, M. K., & Zaman, S. (2016). IoT based autonomous percipient irrigation system using Raspberry Pi. In *Proceedings of the 2016 19th International Conference on Computer and Information Technology (ICCIT)* (pp. 563–568). IEEE.
31. Monica, M., Yeshika, B., Abhishek, G. S., Sanjay, H. A., & Dasiga, S. (2017). IoT based control and automation of smart irrigation system: An automated irrigation system using sensors, GSM, Bluetooth and cloud technology. In *Proceedings of the 2017 International Conference on Recent Innovations in Signal Processing and Embedded Systems (RISE)* (pp. 601–607).
32. Rajalakshmi, P., & Mahalakshmi, S. D. (2016). IoT based crop-field monitoring and irrigation automation. In *Proceedings of the 2016 10th International Conference on Intelligent Systems and Control (ISCO)* (pp. 1–6). IEEE.
33. Vaishali, S., Suraj, S., Vignesh, G., Dhivya, S., & Udhayakumar, S. (2017). Mobile integrated smart irrigation management and monitoring system using IoT. In *Proceedings of the 2017 International Conference on Communication and Signal Processing (ICCSP)* (pp. 2164–2167).
34. Kumar, A., Surendra, A., Mohan, H., Valliappan, K. M., & Kirthika, N. (2017). Internet of Things based smart irrigation using regression algorithm. In *Proceedings of the 2017 International Conference on Intelligent Computing, Instrumentation and Control Technologies (ICICICT)* (pp. 1652–1657).
35. Potamitis, I., Eliopoulos, P., & Rigakis, I. (2017). Automated remote insect surveillance at a global scale and the Internet of Things. *Robotics*, 6(19), 1–14.

36. Rustia, D. J. A., & Lin, T.-T. (2017). An IoT-based wireless imaging and sensor node system for remote greenhouse pest monitoring. *Chemical Engineering*, 58, 601–606.
37. Thorat, A., Kumari, S., & Valakunde, N. D. (2017). An IoT based smart solution for leaf disease detection. In *Proceedings of the 2017 International Conference on Big Data, IoT and Data Science* (pp. 193–198). IEEE.
38. Kapoor, A., Bhat, S. I., Shidnal, S., & Mehra, A. (2016). Implementation of IoT (Internet of Things) and image processing in smart agriculture. In *Proceedings of the International Conference on Computation System and Information Technology for Sustainable Solutions (CSITSS)* (pp. 21–26). IEEE.
39. Rau, A. J., Sankar, J., Mohan, A. R., Krishna, D. D., & Mathew, J. (2017). IoT based smart irrigation system and nutrient detection with disease analysis. In *Proceedings of the 2017 IEEE Region 10 Symposium (TENSYP)* (pp. 1–4). IEEE.
40. Pérez-Expósito, J. S., Fernández-Caramés, T. M., Fraga-Lamas, P., & Castedo, L. (2017). VineSens: An eco-smart decision-support viticulture system. *Sensors*, 17(3), 465.
41. Kim, S., Lee, M., & Shin, C. (2018). IoT-based strawberry disease prediction system for smart farming. *Sensors*, 18(11), 4051.
42. Pourghebleh, B., Wakil, K., & Navimipour, N. J. (2019). A comprehensive study on the trust management techniques in the Internet of Things. *IEEE Internet of Things Journal*, 6(6), 9326–9337.
43. Pourghebleh, B., & Navimipour, N. J. (2017). Data aggregation mechanisms in the Internet of Things: A systematic review of the literature and recommendations for future research. *Journal of Network and Computer Applications*, 97, 23–34.
44. Verdouw, C. N., Wolfert, J., Beulens, A. J. M., & Rialland, A. (2016). Virtualization of food supply chains with the Internet of Things. *Journal of Food Engineering*, 176, 128–136.
45. Hamzei, M., & Navimipour, N. J. (2018). Toward efficient service composition techniques in the Internet of Things. *IEEE Internet of Things Journal*, 5(5), 3774–3787.
46. Liu, Y., Han, W., Zhang, Y., Li, L., Wang, J., & Zheng, L. (2016). An internet-of-things solution for food safety and quality control: A pilot project in China. *Journal of Industrial Information Integration*, 3, 1–7.

MOBILE APPLICATIONS FOR AGRICULTURE, HORTICULTURE AND LIVESTOCK: STATUS, OPERATIONAL PROCEDURES AND WAY FORWARD FOR SMALLHOLDERS

**I. Venkata Reddy*, M. Ravi Kishore, P. N. Siva Prasad,
R. Prabhavathi, N. Rajasekhar, K. Lakshmi Kala and T. Jeswanth Reddy**

ICAR, ATARI Zone-10, ANGRAU, Dr. K. L. Rao Krishi Vigyan Kendra,
Garikapadu, NTR District, Andhra Pradesh, India 521175

*Corresponding author E-mail: ivrexteu18@gmail.com

Abstract

Smallholder farming systems in India and across the world face rising climate risk, volatile markets, and recurring pest, disease and animal-health problems, while conventional extension struggles to reach millions of small and scattered farms. Mobile applications now offer a low-cost route for delivering location-specific weather advisories, plant-health diagnosis, market information, transport services and livestock support directly to the farmer. This chapter reviews the status of farming globally and in India, explains the need for app-based extension, and describes eight widely used applications with step-by-step operational procedures: Meghdoot, Kisan Suvidha and Plantix for crop production; e-NAM and Kisan Rath for horticulture and marketing; and e-Gopala, Bharat Pashudhan (1962 App) and Pashu Poshan for livestock. Adoption barriers such as the rural digital divide, unstable connectivity and low digital literacy are discussed, together with design and institutional strategies to improve uptake. The chapter concludes that apps complement, rather than replace, extension personnel such as Krishi Vigyan Kendras, and that their value depends on local language, simple design and hand-holding support.

Keywords: Mobile Applications, Digital Extension, Smallholder Farmers, Horticulture, Livestock, Climate-Smart Agriculture, Agromet Advisories.

1. Introduction

1.1 Need for Mobile App-Based Extension

Agricultural extension in India has moved through several phases, from village-level visits under the Training and Visit system, to kiosks and call centres, to SMS and voice alerts, and now to smartphone applications (Reddy *et al.*, 2026). Each earlier phase had limits: visits were costly and slow, kiosks required farmers to travel, and SMS and voice messages were restricted by character limits, literacy and advice that was often generalised to the district or state rather than the farmer's own location (Reddy *et al.*, 2026). Smartphone applications can overcome many of these limits because they can be location-specific, updated quickly, multilingual and two-way. The need for mobile-based extension arises from five practical problems faced by small farmers:

- **Weather variability.** Sowing, spraying and irrigation decisions depend on rainfall, temperature and humidity forecasts that are specific to the village or block, not the whole state.
- **Pest, disease and nutrient problems.** Early and correct diagnosis reduces crop loss and avoids unnecessary or wrong pesticide use.
- **Market access and price discovery.** Farmers, especially those growing perishable fruits and vegetables, need reliable price information and a way to reach buyers beyond the local trader.
- **Transport and post-harvest losses.** Horticultural produce loses value quickly; access to suitable transport is essential.
- **Livestock breeding, health and feeding.** Timely vaccination, breeding services and balanced feeding directly affect milk yield and income.

1.2 Status of Farming in The World

There are more than 608 million farms in the world, and over 90 per cent of them are family farms that occupy roughly 70–80 per cent of farmland and produce about 80 per cent of the world's food in value terms (Lowder *et al.*, 2021). Small farms of less than two hectares make up about 84 per cent of all farms but operate only around 12 per cent of agricultural land and produce roughly a third of the world's food, whereas the largest one per cent of farms operate more than 70 per cent of farmland (Lowder *et al.*, 2019; Lowder *et al.*, 2021). Food security remains uneven. The latest United Nations estimate is that about 8.2 per cent of the global population, or roughly 673 million people, faced hunger in 2024, and about 2.3 billion people experienced moderate or severe food insecurity; food insecurity is generally more prevalent in rural areas than in urban areas (FAO *et al.*, 2025). These figures show that the people who produce much of the world's food are also among those most exposed to risk, and that improving the information available to small farms is a global priority.

1.3 Status of Farming in India

Indian agriculture is dominated by small holdings. According to the Agriculture Census 2015–16, the number of operational holdings rose to about 146 million while the average holding size declined from 1.15 hectares in 2010–11 to 1.08 hectares, and the share of women among operational holders increased to about 13.9 per cent (Ministry of Agriculture and Farmers Welfare, 2018). Small and marginal farmers, with less than two hectares, account for about 86 per cent of holdings but operate only about 47 per cent of the cropped area. Agriculture also remains the largest source of employment: the Economic Survey 2024–25 reports that about 46 per cent of the workforce was engaged in agriculture in 2023–24, even though the sector contributes a smaller share, roughly 16 per cent, of gross value added (Ministry of Finance, 2025).

Horticulture (fruits, vegetables, flowers and spices) and livestock are important diversification options for small farms because they can provide more frequent income than a single seasonal crop. At the same time they are more sensitive to delays: fruits and vegetables are perishable, and animals need timely breeding, feeding and health care. Reliable, quickly delivered information is therefore especially valuable in these enterprises. India's small average holding size also means that extension has to reach a very large number of farmers, which makes low-cost digital channels attractive.

1.4 Objectives of the Chapter

This chapter aims to (i) describe selected mobile applications used in crop production, horticulture and livestock in India, (ii) explain how each is operated in practical steps, (iii) summarise the barriers that limit adoption among smallholders, and (iv) suggest ways to improve uptake and impact.

2. Mobile Applications for Crop Production

2.1 Meghdoot

Meghdoot is a weather-based agro-advisory application developed as a joint initiative of the India Meteorological Department (IMD), the Indian Institute of Tropical Meteorology (IITM) and the Indian Council of Agricultural Research (ICAR), with the app built by ICRISAT (ICRISAT, n.d.; Dhulipala *et al.*, 2021). It collects district and crop-wise advisories issued by District Agro-Meteorological Units and Agro Met Field Units every Tuesday and Friday and presents them together with forecast and historical weather information (ICRISAT, n.d.). The app provides forecasts for rainfall, temperature, relative humidity, cloud cover and wind, and offers crop and livestock advisories in local languages (Sharma *et al.*, n.d.; Reddy *et al.*, 2026). For example, instead of only forecasting high humidity, it explains that such weather favours paddy blast and suggests preventive steps (Reddy *et al.*, 2026).

Operational Procedure

- i. Install Meghdoot from the Google Play Store or Apple App Store.
- ii. Select the preferred language and register with name, mobile number, state and district so that the app can show region-specific information (Sharma *et al.*, n.d.).
- iii. Open the weather section to view the current weather and the five-day forecast for the location.
- iv. Open the advisory section, select the crop or livestock category, and read the latest Tuesday or Friday advisory for the district.
- v. Plan sowing, spraying, irrigation or vaccination accordingly, and share the advisory with neighbouring farmers through the app's sharing options.

2.2 Kisan Suvidha

Kisan Suvidha is an omnibus mobile application of the Ministry of Agriculture and Farmers Welfare that brings several services together in one place: current weather and a five-day

forecast with extreme weather alerts, contact details of input dealers, market prices, crop-specific plant protection information, agro-advisories, the Soil Health Card, and information on cold storages and godowns (Ministry of Agriculture and Farmers Welfare, n.d.). Farmers can also contact the Kisan Call Centre from the app and, when a crop looks abnormal, upload a photograph for expert advice. Registration is compulsory (Ministry of Agriculture and Farmers Welfare, n.d.).

Operational Procedure

- i. Download the app for Android or iOS and open it.
- ii. Register by choosing a language and entering mobile number, state, district and block.
- iii. From the home screen select the required service: Weather, Market Prices, Dealers, Plant Protection, Agro Advisories, Soil Health Card, or Cold Storage and Godowns.
- iv. For pest management, choose the crop under Plant Protection and read the recommended practices; if the problem is unclear, upload a clear photograph to send it to agricultural experts.
- v. For marketing, open Market Prices and check the rates of the commodity in nearby markets before deciding when and where to sell.

2.3 Plantix

Plantix is a plant-health application that diagnoses pest damage, diseases and nutrient deficiencies from a photograph of the affected crop and suggests treatment options. Images are analysed by machine-learning models on a server, and the result reaches the farmer within seconds (Rupavatharam *et al.*, 2018; ICRISAT, n.d.). The app also provides a crop calendar, an offline library of pests, diseases and deficiencies, and a community feature to consult experts and other farmers (ICRISAT, n.d.). Its use has been promoted in Andhra Pradesh through partnerships involving ICRISAT and the state government (Rupavatharam *et al.*, 2018).

Operational Procedure

- i. Install Plantix on an Android smartphone with an internet connection.
- ii. Select the language and the crop being grown.
- iii. Choose the health-check (camera) option and photograph the affected leaf, fruit or plant in good daylight, keeping the symptom in focus and filling most of the frame.
- iv. Upload the photograph and wait a few seconds for the diagnosis and treatment suggestions.
- v. Review problem details in the library, try cultural or biological methods first, and consult your local Krishi Vigyan Kendra or agriculture officer before applying chemicals.

3. Mobile Applications for Horticulture and Marketing

Horticultural growers can use Meghdoot, Kisan Suvidha and Plantix for weather, advisories and pest diagnosis. In addition, two applications address the marketing and transport problems that matter most for perishable produce.

3.1 e-NAM (National Agriculture Market)

e-NAM is an online trading platform implemented by the Small Farmers' Agribusiness Consortium (SFAC) that links regulated mandis so that farmers can sell to a wider set of buyers through transparent electronic auctions. More than 1.78 crore farmers and over 4,300 farmer producer organisations were registered on the platform in early 2025 (Small Farmers' Agribusiness Consortium, 2025a). The mobile application offers multilingual support, information on mandis within about 100 km with route maps, prices in nearby e-NAM and non-e-NAM mandis, advance gate entry, tracking of the lot, sampling and assaying facilities, and SMS alerts on the final bid price and receipt of payment (Small Farmers' Agribusiness Consortium, 2025b).

Operational Procedure

- i. Download the e-NAM mobile application and choose Register on the home page (self-registration is possible through the app or portal); enter personal and bank details, upload the required documents and complete registration with the local mandi (APMC) (e-NAM, n.d.; Small Farmers' Agribusiness Consortium, 2025b).
- ii. Before travelling, check prices in nearby e-NAM and non-e-NAM mandis and the route to the nearest mandi.
- iii. Use the advance gate entry option to record the produce and expected arrival.
- iv. At the mandi, the lot is entered, sampled and graded; the farmer can follow the progress of the lot from gate entry to gate exit in the app.
- v. After the e-auction, the farmer sees the winning bid and can accept or reject it (e-NAM, n.d.).
- vi. Payment is credited to the bank account and an SMS confirms the final bid price and payment.

3.2 Kisan Rath

Kisan Rath, developed by the National Informatics Centre and launched by the Ministry of Agriculture and Farmers Welfare in April 2020, helps farmers, farmer producer organisations and traders find transport for agricultural and horticultural produce, including refrigerated (reefer) vehicles for perishables (Ministry of Agriculture and Farmers Welfare, 2020). It supports primary transport from farm to mandis and collection centres and secondary transport from mandis to other markets, processing units and warehouses.

Operational Procedure

- i. Install Kisan Rath and select the language.
- ii. Register as a farmer, trader or transport service provider (transporters also register their vehicles) and log in.
- iii. Post the load requirement, giving the produce, quantity, whether part or full load, and the pick-up and destination points.

- iv. Transporters registered on the app respond with contact details and quotations; compare the responses.
- v. Contact the chosen transporter, finalise the arrangement, and rate the service after the trip.

4. Mobile Applications for Livestock

4.1 e-Gopala

e-Gopala was developed by the National Dairy Development Board (NDDB) as a breed-improvement marketplace and information platform for dairy farmers. It helps farmers manage livestock, buy and sell disease-free germplasm such as semen and embryos, find quality breeding services including artificial insemination, vaccination and treatment, and receive guidance on animal nutrition and ethno-veterinary care. It sends alerts for due dates of vaccination, pregnancy diagnosis and calving and informs farmers about government schemes (National Dairy Development Board, 2021).

Operational Procedure

- i. Install the e-Gopala application (or open its web version) and register as a farmer user as prompted.
- ii. Add the details of the animals so that reminders can be generated.
- iii. Use the breeding section to look for germplasm and the nearest artificial insemination or veterinary service.
- iv. Use the nutrition and treatment sections for feeding guidance and first-aid or ethno-veterinary information.
- v. Watch for alerts on vaccination, pregnancy diagnosis and calving, and act on them in time.

4.2 Bharat Pashudhan and the 1962 App

Bharat Pashudhan is a technology-enabled, farmer-centred digital ecosystem for the livestock sector run by the Department of Animal Husbandry and Dairying and NDDB. Each animal is given a unique identification (Pashu Aadhaar) linked to an ear tag, and services such as vaccination, breeding and treatment are recorded against that identity so that they are visible to the farmer and to field veterinarians (Department of Animal Husbandry and Dairying & National Dairy Development Board, n.d.). More than 35 crore animals have been issued Pashu Aadhaar under the National Digital Livestock Mission (Press Information Bureau, 2026). The 1962 App gives farmers authenticated information on livestock practices and schemes, and the ration balancing software has been revamped and incorporated into the system (National Dairy Development Board, n.d.).

Operational Procedure

- i. Ask the field veterinarian or livestock assistant to tag the animal and register it so that a unique identification is generated.

- ii. Install the farmer application (1962 App) and log in with the registered mobile number.
- iii. Search the animal by its tag identification to view the vaccination, breeding and treatment records.
- iv. Use the information and ration-balancing options for guidance on management and feeding.
- v. Ensure that the field worker records every new service (vaccination, artificial insemination, treatment) against the same identification.

4.3 Pashu Poshan

Pashu Poshan is an Android-based application from NDDB that formulates a cost-optimised balanced ration for dairy animals from locally available feed ingredients, considering the animal's species (cattle or buffalo), age, milk yield, milk fat and feeding regime, and advises adjustment of feed quantities along with an area-specific mineral mixture (National Dairy Development Board, n.d.). Under Phase I of the National Dairy Plan, the Ration Balancing Programme covered about 28.65 lakh milch animals of 21.57 lakh farmers in 18 states and, on average, raised daily milk yield by 0.27 kg per animal, reduced feeding cost by 11.8 per cent, increased net income by about Rs. 27 per animal per day and reduced enteric methane emission by 13.7 per cent (National Dairy Development Board, n.d.).

Operational Procedure

- i. Install Pashu Poshan on an Android phone, or register on the NDDB INAPH portal, and log in.
- ii. Enter the animal profile: cattle or buffalo, age, daily milk yield, milk fat and current feeding practice.
- iii. Enter the feed and fodder ingredients that are locally available, with the quantities normally fed.
- iv. Generate the ration; the software suggests quantities of each ingredient and the mineral mixture at least cost.
- v. Feed as advised, record milk yield and feed cost over the following weeks, and revisit the ration when the stage of lactation or feed prices change.

4.4 Summary of the Applications

Table 1 summarises the applications discussed.

Table 1: Selected mobile applications and their main uses

Application	Developed / Managed By	Sector	Main Use
Meghdoot	IMD, IITM, ICAR; built by ICRISAT	Crops, livestock	Five-day weather forecast and twice-weekly district agro-advisories
Kisan Suvidha	Ministry of Agriculture and Farmers Welfare	Crops, general	Weather, prices, dealers, plant protection, Soil Health Card

Plantix	PEAT; customised with ICRISAT and partners	Crops, horticulture	Photo-based diagnosis of pests, diseases and deficiencies
e-NAM	SFAC, Ministry of Agriculture and Farmers Welfare	Marketing, horticulture	Online mandi trading, price information, lot tracking
Kisan Rath	National Informatics Centre; Ministry of Agriculture and Farmers Welfare	Horticulture, marketing	Finding transport, including reefer vehicles
e-Gopala	NDDB	Livestock	Breeding services, germplasm, health and nutrition alerts
Bharat Pashudhan / 1962 App	DAHD and NDDB	Livestock	Animal identification, service records, information
Pashu Poshan	NDDB	Livestock	Least-cost balanced ration for dairy animals

5. Adoption Barriers and Strategies for Improvement

Even well-designed applications have limited impact if smallholders cannot or do not use them. Reddy *et al.* (2026) identify three groups of barriers. The first is socio-economic and infrastructural: smartphone ownership and data affordability remain unequal, particularly for women and marginal farmers, remote farmland often has unstable network connectivity, and household phones are frequently controlled by male family members. The second is cognitive: many older farmers have low digital self-confidence, and registration screens that require selecting state, district, block, crop and variety through drop-down menus create friction for semi-literate users. The third concerns trust and data quality: advisories that do not match the microclimate of the farmer's village, or that arrive after inputs have already been applied, reduce confidence in digital recommendations.

The same authors recommend several design responses that apply to all the applications above (Reddy *et al.*, 2026):

- Replace text-heavy screens with locally meaningful icons and traffic-light colour codes (green for favourable, amber for caution, red for immediate threat).
- Provide voice search in local dialects and a “play audio” option for every advisory.
- Build offline-first features that store the latest forecasts and advisories on the phone, and keep the application light so that it runs on low-cost handsets.

Institutional support is equally important. Krishi Vigyan Kendras, extension officers, farmer producer organisations, self-help groups and progressive farmers can demonstrate the applications in the village, help with registration, and make sure that women and older farmers

are included. Farmers should treat any diagnosis or advisory from an application as a first opinion and confirm it locally before taking costly decisions such as spraying pesticides or selling animals.

Conclusion

Small farms dominate agriculture in the world and in India, and they carry much of the risk associated with weather, pests, markets and animal health. Mobile applications such as Meghdoot, Kisan Suvidha, Plantix, e-NAM, Kisan Rath, e-Gopala, Bharat Pashudhan and Pashu Poshan bring timely, location-specific information and services to the farmer's hand at low cost, covering crops, horticulture and livestock. Their operation is generally simple: install, register, select the crop or animal, and act on the advice or service offered. However, their benefit reaches farmers only when language, literacy, connectivity and gender barriers are addressed and when local extension staff help farmers to use them. Future development should focus on voice-based and offline access, better spatial resolution of advisories, integration of services (weather, markets and animal records) in fewer applications, and continuous feedback from farmers.

References

1. Department of Animal Husbandry and Dairying, & National Dairy Development Board. (n.d.). *Bharat Pashudhan: A technology-enabled, farmer-centric digital ecosystem for the livestock sector*. Bharat Pashudhan Portal.
2. Dhulipala, R. K., Gogumalla, P., Rao, K. P. C., Palanisamy, R., Smith, A., Nagaraji, S., Rao, S. A., Vishnoi, L., Singh, K. K., Bhan, S. C., & Whitbread, A. M. (2021). *Meghdoot—A mobile app to access location-specific weather-based agro-advisories pan India*. Working Paper. ICRISAT/CGIAR. <https://oar.icrisat.org/11917>
3. e-NAM. (n.d.). *Farmers module, e-NAM mobile app*. National Agriculture Market. <https://agri.enam.gov.in/mobile-app/farmers-module>
4. FAO, IFAD, UNICEF, WFP, & WHO. (2025). *The state of food security and nutrition in the world 2025*. Food and Agriculture Organization of the United Nations.
5. ICRISAT. (n.d.). *Meghdoot weather-based mobile application*. ICRISAT Press Room. <https://pressroom.icrisat.org/meghdoot-weather-based-mobile-application>
6. ICRISAT. (n.d.). *Plant protection application app: Plantix*. ISSCA Scalable Solutions. <https://issca.icrisat.org/scalable-solutions/plant-protection-application-app-plantix>
7. Lowder, S. K., Sánchez, M. V., & Bertini, R. (2019). *Farms, family farms, farmland distribution and farm labour: What do we know today?* FAO Agricultural Development Economics Working Paper 19-08. FAO.
8. Lowder, S. K., Sánchez, M. V., & Bertini, R. (2021). Which farms feed the world and has farmland become more concentrated? *World Development*, 142, 105455.
9. Ministry of Agriculture and Farmers Welfare. (2018). *Agriculture Census 2015–16: Provisional results on number and area of operational holdings*. Government of India.

10. Ministry of Agriculture and Farmers Welfare. (2020, April 17). “*Kisan Rath*” mobile app to facilitate transportation of farm produce. Press Information Bureau, Government of India.
11. Ministry of Agriculture and Farmers Welfare. (n.d.). *Kisan Suvidha* mobile app. mKisan Portal. <https://mkisan.gov.in/Home/Downloads>
12. Ministry of Finance. (2025). *Economic Survey 2024–25*. Government of India.
13. National Dairy Development Board. (2021, August 28). *Union Minister of Fisheries, Animal Husbandry and Dairying launches web version of NDDB-developed e-GOPALA application and IMAP web portal*. <https://nddb.coop/node/2246>
14. National Dairy Development Board. (n.d.). *Ration Balancing Programme and Pashu Poshan*. <https://www.nddb.coop/services/animalnutrition/programmes/ration-balancing-programme>
15. Press Information Bureau. (2026, January). *National Digital Livestock Mission and Bharat Pashudhan*. Government of India.
16. Reddy, I. V., Prabhavathi, R., & Kishore, M. R. (2026). Empowering smallholders through app-based extension: A case study of mobile agromet advisory services. In C. Sreelatha, S. Lalwani, M. Raju, & N. H. Vasoya (Eds.), *Future of AI and data science: Transforming industries and society, Volume I* (pp. 118–123). Bhumi Publishing. ISBN 978-93-47587-24-5.
17. Rupavatharam, S., Kennepohl, A., Kummer, B., & Parimi, V. (2018). Automated plant disease diagnosis using innovative Android app (Plantix) for farmers in the Indian state of Andhra Pradesh. *Phytopathology*, 108(10).
18. Sharma, Ph. R., Walling, I., Seyie, A., Yanthan, A. W., & Rajkhowa, D. J. (n.d.). *Meghdoot app—A mobile app to assist farmers for weather-based farm management*. ICAR Nagaland Centre.
19. Small Farmers’ Agribusiness Consortium. (2025a). *Reply to Lok Sabha Question No. 4818 dated 04.03.2025 on participation of farmers in e-NAM platform*. SFAC.
20. Small Farmers’ Agribusiness Consortium. (2025b). *Reply to Lok Sabha Question No. U11382 dated 20.03.2025 on e-NAM*. SFAC.

DIGITAL EXTENSION DELIVERY: MOBILE APPLICATIONS, WHATSAPP GROUPS, AND VIDEO ADVISORIES REDEFINING FARMER CONTACT IN NEXT-GENERATION AGRICULTURE

K. Achuta Raju^{*1}, I. Venkata Reddy² and R. Praveen Babu³

¹DAATTC, Bapatla, Andhra Pradesh, India

²K.L. Rao Krishi Vigyan Kendra, Garikapadu, NTR District, Andhra Pradesh, India

³Krishi Vigyan Kendra, Pandirimamidi, East Godavari District, Andhra Pradesh, India

*Corresponding author E-mail: katchutaraju@angrau.ac.in

Abstract

Agricultural extension has long depended on face-to-face contact between farmers and extension officers, a model that is expensive to run and structurally unable to reach the majority of smallholder households in a timely manner. This chapter examines the ongoing shift toward digital extension delivery through mobile applications, WhatsApp groups, and video advisories, situating these channels within the wider movement toward smart farming and next-generation agriculture. Drawing on recent empirical evidence from India, Sub-Saharan Africa, Southeast Asia, and China, the chapter explains how each channel functions, reviews documented gains in farmer knowledge, technology adoption, and productivity, and presents case studies covering phone-based advisory platforms, farmer-led WhatsApp networks, and participatory video models. It closes by examining persistent barriers, including digital divides, misinformation, message overload, and gender gaps, alongside emerging opportunities such as generative artificial intelligence advisory tools, arguing that digital and traditional extension are best combined rather than treated as substitutes for one another.

Keywords: Digital Extension, Mobile Applications, Whatsapp Groups, Video Advisories, Smart Farming.

1. Introduction

Extension services have historically been the primary bridge between agricultural research and farm-level practice. In the conventional model, a trained extension officer visits villages, conducts demonstrations, and answers farmer queries in person, a system anchored in the assumption that reliable knowledge transfer requires physical presence. This model has delivered real benefits over the past century, but it scales poorly. In most developing regions, the ratio of extension staff to farm households remains extremely low, travel budgets are limited, and a single officer may be responsible for thousands of farmers spread across a wide and often difficult terrain. As a result, many smallholders receive advice that is delayed, generic, or simply

unavailable at the moment a decision must be made, whether that decision concerns pest outbreaks, irrigation timing, or input purchases.

The rapid spread of mobile telephony and, more recently, affordable smartphones and mobile data has opened an alternative pathway. Global development organisations report that phone-based agricultural advisory services now reach tens of millions of farmers across Asia and Africa, with Precision Development (PxD) alone estimated to serve more than 18.5 million farmers as of 2024 through evidence-informed mobile extension services. This growth reflects a broader recognition that mobile phone-based extension can be an efficient and cost-effective way of delivering tailored, timely agricultural information at a scale that in-person visits cannot match.

This chapter focuses on three interlinked digital channels that are together redefining how extension messages reach farmers: purpose-built mobile applications, informal and institutional WhatsApp groups, and short instructional videos distributed either through dedicated platforms or through chat applications. These channels are not always distinct in practice; a single farmer may receive weather alerts through an app, discuss a pest problem in a WhatsApp group, and watch a demonstration video shared within that same group. The chapter treats them together because their convergence, rather than any one technology in isolation, is what is reshaping farmer contact in the smart farming era.

The remainder of the chapter is organised as follows. Section 2 outlines the limitations of traditional extension and the broader rise of information and communication technology (ICT) in agriculture. Sections 3 to 5 examine mobile applications, WhatsApp groups, and video advisories in turn, describing their working mechanisms and reviewing recent empirical evidence of their effects. Section 6 presents illustrative case studies drawn from India, Ethiopia, China, Tanzania, and Burkina Faso. Section 7 discusses the barriers that continue to constrain digital extension and the research and policy directions that follow, and Section 8 concludes.

The chapter's broader argument is situated within the concept of smart farming, understood here as the integration of digital technologies, including sensors, data analytics, and communication platforms, into the full range of farm decision-making rather than into production alone. Extension delivery is often treated as a secondary concern within smart farming discussions, which tend to emphasise precision inputs, remote sensing, and automation. This chapter argues that the communication layer connecting farmers to expertise and to one another deserves equal attention, since even the most sophisticated sensing technology delivers little value if the resulting recommendation cannot reach the farmer who needs to act on it within a relevant time window.

2. The Changing Landscape of Agricultural Extension

2.1 Limitations of the Traditional Model

Public agricultural extension systems in most low- and middle-income countries were designed for an era of far smaller and more static farming populations. Extension workers are frequently required to cover very large areas with limited transport, and their visits, when they occur, tend to follow standardised messaging that does not account for hyper-local conditions such as microclimate, soil variability, or the specific pest pressure affecting an individual field in a given week. Because advice is not always timely, farmers often make critical decisions, such as when to apply fertiliser or how to respond to an emerging disease, without access to expert input at the point where it would be most useful.

These structural constraints have long been recognised in the extension literature, which has repeatedly called for models that are more scalable, more responsive, and less dependent on a fixed cadre of field staff. It is against this backdrop that digital tools have been adopted not as a replacement for human expertise but as a mechanism for extending its reach.

2.2 The Rise of ICT-Enabled and Digital Extension

Digital extension tools (DETs) are commonly defined as digital platforms through which farmers or other actors in the agricultural knowledge system access, discuss, or share farming information. A systematic review of 141 studies covering the period 2005 to 2021 identified thirteen distinct opportunities associated with interactive digital extension services, including their usefulness for learning, peer exchange, and knowledge co-creation, alongside twenty-one recurring barriers such as poor connectivity, low digital literacy, and the absence of two-way interaction in many services. This body of evidence indicates that digital extension is neither a uniformly positive nor a uniformly problematic development; its outcomes depend heavily on design choices, institutional backing, and the local infrastructure within which it is deployed.

Within this broader category, three channels have become especially prominent and are the focus of this chapter: dedicated mobile applications built specifically for agricultural advisory purposes, general-purpose chat applications such as WhatsApp that have been repurposed by farmers and extension actors for agricultural knowledge sharing, and short instructional videos distributed either through structured programmes or informally through social media and chat platforms.

2.3 Traditional Contact Methods Being Replaced or Supplemented

It is worth being precise about what is being replaced. Traditional farmer contact methods include scheduled village-level meetings, farmer field schools, one-on-one farm visits by extension officers, radio broadcasts, printed bulletins, and, in some systems, toll-free advisory call centres. Several of these methods remain valuable and are not disappearing; call centre models such as India's Kisan Call Centre scheme, for example, have continued to attract heavy

usage, with national review bodies reporting that the scheme received more than five million calls in a single year. What has changed is the balance of channels through which the first point of contact now occurs. Increasingly, a farmer's first source of information about a new pest outbreak or a price change is a WhatsApp message, a mobile application alert, or a shared video rather than a scheduled visit, even where the underlying expertise and institutional structure supporting that message still originates from the same extension system.

This shift in the point of first contact carries several implications. It compresses the time between the emergence of a problem and the delivery of relevant advice, it allows a single piece of expert content to reach many more farmers than a single officer could visit in the same period, and it creates new forms of farmer-to-farmer knowledge exchange that occur independently of any extension officer's involvement. At the same time, it introduces new intermediaries, including the designers of mobile applications, the administrators of WhatsApp groups, and the producers of instructional videos, whose incentives and quality control practices may differ substantially from those of a public extension service.

3. Mobile Applications as a Digital Extension Channel

3.1 Working Mechanism and Core Features

Agricultural mobile applications typically combine several functions within a single interface: localized weather forecasts, crop-specific advisories, pest and disease identification support, market price information, and increasingly, direct connections to buyers and financial services. By consolidating information that would otherwise require multiple separate visits or phone calls, these applications allow farmers to access decision-relevant information at the moment of need rather than waiting for the next scheduled extension visit. Recent analyses emphasise that the value of such applications lies not merely in information provision but in the way they support market linkages, price transparency, and access to mobile banking and digital payment services, thereby connecting advisory content to the broader economic decisions farmers must make.

In several deployments, extension officers use the same applications to disseminate advisory content directly through text, audio, and video messages, effectively turning the mobile application into a channel for both institutional messaging and farmer-initiated queries. This dual function, information push from experts and information pull by farmers, is what most clearly differentiates modern agricultural applications from earlier, one-directional SMS advisory services.

3.2 Empirical Evidence of Impact

Evidence on the effects of mobile application-based extension is growing steadily. In Southwest Nigeria, a 2024 study of smallholder farmers found that greater exposure to agricultural smartphone applications was associated with higher rates of adoption and with measurable gains

in total factor productivity and technical efficiency, suggesting that awareness and familiarity, not just availability, are important preconditions for impact. In China, a household-level survey of 400 farmers in Zhejiang province examined the effects of the 'Zhe'yang'shi' WeChat-based advisory application on the adoption of soil testing and formula fertilisation, a precision fertiliser technology; the results showed that use of the application significantly increased adoption of this practice, with effects that varied across farms of different production scales.

Questions of financial sustainability have also begun to receive attention. A 2024–2025 study using a Becker–DeGroot–Marschak elicitation experiment in Tanzania and Burkina Faso examined smallholder farmers' willingness to pay for a digital extension platform named *farmbetter*, reflecting a growing interest among implementers in understanding whether farmers themselves would sustain such services financially once donor or government subsidies are withdrawn. Such studies mark an important shift in the digital extension literature, from questions of whether these tools work toward questions of how they can be financed and scaled responsibly over the long term.

4. WhatsApp Groups: Peer-to-Peer and Institutional Advisory Networks

4.1 Mechanism and Patterns of Use

Unlike purpose-built applications, WhatsApp and similar chat platforms were not designed for agricultural advisory purposes, yet they have been adopted extensively by farmers, extension workers, and researchers precisely because they are already installed on the smartphones farmers own, require no additional training to operate, and support text, images, voice notes, and video within a single low-bandwidth-friendly interface. Groups are typically organised around a village, a crop, or an extension officer's caseload, and they support both one-to-many broadcast messaging from experts and many-to-many peer discussion among farmers themselves.

Recent review synthesising research published between 2015 and 2026 on the use of WhatsApp groups for agricultural information dissemination in India concluded that multimedia-supported advisories delivered through such groups substantially improve farmer participation, real-time communication, and information sharing, while also enhancing decision-making, peer learning, and social network formation among members. The same review cautioned that these benefits coexist with recognised drawbacks, including the spread of inaccurate information, message overload, and the exclusion of farmers on the wrong side of the digital divide.

4.2 Evidence from Field Studies

One of the most detailed empirical studies of WhatsApp-based extension was conducted across eight districts of Himachal Pradesh, India, where researchers created dedicated WhatsApp and Facebook groups among smartphone-owning farmers and tracked their use over a six-month period. Farmers exchanged several hundred posts during the study, with the largest shares of queries relating to animal husbandry and crop farming, and reported benefits including faster

access to solutions for crop and livestock losses, multimodal information delivery, and the formation of social capital among members. The study also found that internet connectivity remained a binding constraint, with a large majority of respondents calling for improved connectivity after experiencing slow, unreliable mobile networks during the intervention.

WhatsApp groups have also proven effective as conduits for sharing instructional video content rather than text alone. A study of 294 extension workers in Bihar, India, who were asked to circulate three wheat agronomy videos found that WhatsApp was the dominant channel used, accounting for the large majority of surveyed sharing instances, because it allowed extension workers to reach farmers they already knew and trusted with minimal additional effort. This finding underscores an important point that recurs throughout the digital extension literature: technology adoption is mediated as much by existing social relationships and trust as by the technical features of the platform itself.

5. Video Advisories: Participatory and Emerging AI-Enabled Extension

5.1 The Participatory Video Model

Among video-based extension approaches, the model pioneered by the organisation Digital Green has generated the most extensive body of rigorous evidence. The approach features local farmers, often women, demonstrating agricultural practices in short videos that are then screened to other farmers, typically in small group settings facilitated by a community mediator who can pause the video and answer questions. This participatory design is intended to increase the credibility and relevance of the content relative to generic, top-down advisory messaging. Reports indicate that Digital Green's video-mediated extension model has reached more than seven million smallholder farmers in India and other countries.

A cluster-randomised evaluation of Digital Green's approach in Ethiopia, published in *World Development*, examined the effects of video-mediated extension following the programme's expansion into sixty-eight woredas across four of the country's most agriculturally important regions and provided evidence on both technology adoption outcomes and the gendered dimensions of extension delivery. An independent technical evidence review compiled by IDinsight in 2023 synthesised results from multiple such evaluations and concluded that Digital Green's video-mediated approach generally produces gains in farmer knowledge and, in a number of contexts, in adoption of recommended practices, while also noting that impacts vary depending on the strength of the underlying extension programme into which the videos are embedded.

5.2 Video Dissemination through Chat Applications

Beyond formally organised screening programmes, farming videos are increasingly shared informally through chat applications and social media, a development that has attracted growing scholarly attention. Research on extension workers in Bihar found that these workers did not

deploy shared videos uniformly; instead, they adapted the practice according to their own goals, sometimes reinforcing official advisory messages and at other times repurposing content for unrelated ends, with implications for how service managers should think about video-sharing as an extension strategy rather than treating it as a simple broadcast tool. Farmers and other actors have also begun producing and distributing their own advisory videos independent of formal programmes; one widely cited example is a farmer from Punjab whose independently produced farming advisory videos attracted a subscriber base in the millions, illustrating how video-based knowledge sharing has expanded well beyond the boundaries of any single institutional programme.

5.3 Toward Generative AI-Enabled Advisory Tools

The most recent development in this space is the emergence of generative artificial intelligence advisory tools that combine the immediacy of a chat interface with the depth of an expert knowledge base. Digital Green, in partnership with Microsoft Research, has developed and deployed one such tool, Farmer.Chat, across several countries, and case-study analysis of its use has examined how conversational AI can support, or in some cases limit, farmer learning, trust-building, and knowledge co-creation relative to earlier video- and chat-based approaches. While still at an early stage, this line of development suggests that the boundary between mobile applications, chat-based advisory, and video content is likely to blur further as AI-enabled assistants begin to synthesise all three formats within a single conversational interface.

6. Case Studies and Applications

The following cases illustrate how digital extension delivery has been implemented and evaluated across different regions and channels. Together, they show a common pattern: the most durable initiatives tend to combine a digital channel with a structured institutional programme rather than relying on the technology alone to generate impact.

The PxD and farmbetter cases show two different stages in the maturity of mobile-application-based extension. PxD's evolution from a research-driven pilot founded in 2016 into a service reaching over 18.5 million farmers by 2024 demonstrates that phone-based advisory models can scale substantially once the underlying advisory content and delivery mechanism have been validated. farmbetter's willingness-to-pay research in Tanzania and Burkina Faso represents an earlier and equally important stage, in which implementers are testing not whether farmers value a service, but whether farmers are willing to fund it themselves, a question that will determine whether such platforms can eventually operate without continuous donor support.

The Zhejiang WeChat case is instructive because it shows digital extension operating within a very different institutional and infrastructural context from the Indian and African examples. China's relatively high smartphone penetration and integration of agricultural advisory functions into an already dominant messaging application, rather than a stand-alone agricultural app,

suggests that the choice of platform is often shaped by pre-existing digital habits in a given country rather than by the specific requirements of agricultural communication.

The Himachal Pradesh and Bihar cases together illustrate the dual character of WhatsApp as an extension channel: in Himachal Pradesh, farmers used dedicated groups primarily for two-way, peer-supported problem solving around livestock and crop issues, while in Bihar, WhatsApp functioned mainly as a distribution channel for video content produced elsewhere, moved through networks of pre-existing trust between extension workers and farmers. Both cases point to the same underlying mechanism: WhatsApp's value in extension arises less from any feature specific to the application and more from its ability to piggyback on relationships and networks that already existed before the technology was introduced.

Finally, the Digital Green and Farmer.Chat cases mark two ends of a continuum in video-based and AI-enabled advisory delivery. Digital Green's participatory video model, built around locally produced content and community-level facilitation, has accumulated over a decade of rigorous evaluation evidence, including the Ethiopian cluster-randomised trial and the 2023 IDinsight evidence synthesis. Farmer.Chat, by contrast, represents an attempt to compress the video, chat, and expert-query functions of the previous models into a single conversational interface powered by generative AI, and remains at a much earlier stage of independent evaluation. Read together, these cases suggest that future digital extension design is likely to move toward integrated platforms that combine several of these formats rather than treating mobile applications, WhatsApp groups, and videos as separate channels.

- Precision Development (PxD), Asia and Africa: A mobile phone-based advisory service founded in 2016 that has scaled to reach over 18.5 million farmers by the end of 2024, delivering both directly to farmers and through digital agriculture services transferred to government partners.
- farmbetter, Tanzania and Burkina Faso: A digital extension platform evaluated through a willingness-to-pay experiment (2024–2026) to test the financial sustainability of farmer-funded digital advisory models in Sub-Saharan Africa.
- 'Zhe'yang'shi' WeChat Application, Zhejiang, China: A smartphone-based digital extension service shown, through a 2022 household survey of 400 farmers, to significantly increase adoption of soil testing and precision fertilisation practices.
- WhatsApp and Facebook Extension Groups, Himachal Pradesh, India: A six-month, quasi-experimental intervention across eight districts and 96 farmers demonstrating gains in knowledge sharing, peer learning, and social capital, alongside persistent connectivity constraints.
- Digital Green Video-Mediated Extension, Ethiopia and India: A participatory video model, evaluated through cluster-randomised trials, that has reached more than seven

million farmers and demonstrated gains in productivity and, in the Ethiopian case, in farmer technology adoption following programme expansion.

- WhatsApp-Mediated Video Sharing, Bihar, India: A study of 294 extension workers sharing wheat agronomy videos, finding that the majority of video dissemination occurred through WhatsApp because it leveraged extension workers' pre-existing relationships of trust with farmers.
- Farmer.Chat, Multi-Country Deployment: A generative AI-powered advisory chatbot developed by Digital Green and Microsoft Research, illustrating the next stage of convergence between mobile, chat, and video-based extension formats.

7. Future Horizons and Challenges

7.1 Persistent Barriers

Despite encouraging results, digital extension delivery continues to face several well-documented barriers. Connectivity remains uneven in many rural areas, with farmers in some studies reporting reliance on slow second-generation mobile networks that limit the practical usefulness of video and image-heavy content. Digital literacy and access to appropriate devices are not evenly distributed, and evidence from South and Southeast Asia points to a persistent gender gap in smartphone ownership and digital extension use, which risks reinforcing existing inequities in access to agricultural knowledge and resources rather than closing them. Message overload and the spread of inaccurate or unverified information within informal WhatsApp groups have also been identified as recurring concerns, particularly where groups lack moderation by a trained facilitator or institutional partner.

A further challenge concerns financial and institutional sustainability. Many digital extension initiatives have relied heavily on donor or government funding during their pilot and early scale-up phases, and questions remain about whether farmers themselves are willing and able to pay for these services once external support is reduced. The systematic review of interactive digital extension services noted the frequent absence of two-way interaction and centralised coordination between farmers and service providers as a structural weakness that limits the long-term effectiveness of many platforms.

7.2 Directions for Research and Practice

Several directions appear promising for future research and practice. First, hybrid models that combine digital channels with periodic in-person contact, rather than treating digital and traditional extension as substitutes, appear best positioned to preserve the trust and contextual judgement that trained extension officers provide while extending reach through mobile applications, WhatsApp groups, and videos. Second, greater attention to gender-responsive design, including content and delivery formats tailored to women farmers' access constraints, is needed given the documented gender gaps in digital extension uptake. Third, the emergence of

generative AI advisory tools such as Farmer.Chat calls for continued independent evaluation of how conversational AI affects farmer trust, learning, and the quality of knowledge co-creation relative to established video- and chat-based approaches. Finally, research on farmers' willingness to pay for digital extension services, still described in the literature as limited, deserves further attention if these platforms are to move toward durable, less donor-dependent business models.

Conclusion

Mobile applications, WhatsApp groups, and video advisories have moved from experimental pilots to substantial components of agricultural extension systems across Asia and Africa, collectively reaching tens of millions of farmers and generating a growing and increasingly rigorous body of evidence on their effects. Each channel brings distinct strengths: mobile applications consolidate advisory content with market and financial services, WhatsApp groups leverage existing social trust for rapid, peer-supported information exchange, and video advisories combine visual demonstration with participatory credibility. Yet none of these channels functions as a complete substitute for the human expertise, contextual judgement, and trust that traditional extension officers provide, and each carries its own risks, from misinformation to unequal access. As the sector moves toward next-generation, AI-enabled advisory tools, the central lesson from the evidence reviewed in this chapter is that digital extension delivers the greatest benefit for smallholder farmers when it is designed to complement, rather than replace, the broader extension system within which it operates.

References

1. Abate, G. T., Bernard, T., Makhija, S., & Spielman, D. J. (2023). Accelerating technical change through ICT: Evidence from a video-mediated extension experiment in Ethiopia. *World Development*, 161, 106089. <https://doi.org/10.1016/j.worlddev.2022.106089>
2. Balaji, G., & Kavaskar, M. (2024). An analysis of farmer's perception towards WhatsApp as a farm technology dissemination tool. *Journal of Experimental Agriculture International*, 46(9), 330–335.
3. Coggins, S., Steinke, J., Van Etten, J., Vernooy, R., & Bentley, J. (2022). How have smallholder farmers used digital extension tools? Developer and user voices from Sub-Saharan Africa, South Asia and Southeast Asia. *Agricultural Systems*, 196, 103352.
4. Kamal, M., & Bablu, T. A. (2023). Mobile applications empowering smallholder farmers: An analysis of the impact on agricultural development. *International Journal of Social Analytics*, 8(6), 36–52.
5. Kolapo, A., & Didunyemi, A. J. (2024). Effects of exposure on adoption of agricultural smartphone apps among smallholder farmers in Southwest, Nigeria: Implications on farm-

- level efficiency. *Agriculture & Food Security*, 13(1), 1–20. <https://doi.org/10.1186/s40066-024-00485-1>
6. Nain, M. S., Singh, R., Mishra, J. R., & Sharma, J. P. (2019). Social networking of innovative farmers through WhatsApp messenger for learning exchange: A study of content sharing. *Indian Journal of Agricultural Sciences*, 89(3), 556–559.
 7. Sen, L. T. H., Phuong, L. T. H., Chou, P., Dacuyan, F. B., Nyberg, Y., & Wetterlind, J. (2025). The opportunities and barriers in developing interactive digital extension services for smallholder farmers as a pathway to sustainable agriculture: A systematic review. *Sustainability*, 17(7), 3007. <https://doi.org/10.3390/su17073007>
 8. Sherpa, S. R., & Craufurd, P. (2024). How do chat apps support the use of farming videos in agricultural extension? A case study from Bihar, India. *Journal of Agricultural Education and Extension*. Advance online publication. <https://doi.org/10.1080/27685241.2024.2420803>
 9. Thakur, D., & Chander, M. (2018). Social media in agricultural extension: Benefits and challenges under Indian context. *Asian Journal of Agricultural Extension, Economics & Sociology*, 27(2), 1–8. <https://doi.org/10.9734/AJAEES/2018/44086>
 10. Wang, X., Yan, W., & Zhou, J. (2022). Influence of smartphone-based digital extension service on farmers' sustainable agricultural technology adoption in China. *International Journal of Environmental Research and Public Health*, 19(15), 9576.
 11. Wetterlind, J., et al. (2024). Barriers and enablers of digital extension services' adoption among smallholder farmers: The case of Cambodia, the Philippines and Vietnam. *International Journal of Agricultural Sustainability*, 22(1), 2368351. <https://doi.org/10.1080/14735903.2024.2368351>

FARMER PRODUCER ORGANIZATIONS (FPOS) AS A BRIDGE TO NEXT-GENERATION AGRI-TECH

K. Achuta Raju*¹, I. Venkata Reddy² and R. Praveen Babu³

¹DAATTC, Bapatla, Andhra Pradesh, India

²K.L. Rao Krishi Vigyan Kendra, Garikapadu, NTR District, Andhra Pradesh, India

³Krishi Vigyan Kendra, Pandirimamidi, East Godavari District, Andhra Pradesh, India

*Corresponding author E-mail: k.catchutaraju@angrau.ac.in

Abstract

Indian agriculture is dominated by small and marginal holdings, a structure that has historically limited the reach of capital-intensive and knowledge-intensive innovations to individual farmers. Farmer Producer Organizations (FPOs) have emerged over the last decade as the principal institutional vehicle for aggregating these scattered holdings into economically viable collectives. This chapter examines the evolving role of FPOs as an intermediary structure that connects smallholders with next-generation agricultural technologies, including precision agriculture tools, remote sensing and drone-based services, artificial-intelligence-driven advisories, digital marketing platforms and agri-fintech products. Drawing on the national experience of the Central Sector Scheme for the formation of 10,000 FPOs and on field-level extension work carried out through Krishi Vigyan Kendras (KVKs), the chapter identifies the specific mechanisms through which FPOs de-risk, subsidize and simplify technology adoption for their member farmers: pooled investment in shared machinery and digital infrastructure, aggregated data that make customized advisories viable, collective bargaining that attracts agri-tech start-ups and input companies, and handholding support that builds digital literacy. The chapter also outlines persistent constraints, such as thin management capacity, uneven connectivity and financing gaps, and closes with recommendations for strengthening the FPO–agri-tech interface through convergence with public extension systems.

Keywords: Farmer Producer Organizations, Agri-Tech, Precision Agriculture, Agricultural Extension, Digital Agriculture, Smallholder Farmers, Krishi Vigyan Kendra.

1. Introduction

The structure of Indian agriculture, with an overwhelming majority of operational holdings classified as small or marginal, has long been recognized as a constraint on the diffusion of modern technology. Individual smallholders typically lack the capital to invest in machinery, sensors or digital subscriptions, the volume of produce needed to interest input suppliers or buyers in customized service, and the technical literacy to interpret and act on data-driven recommendations. Farmer Producer Organizations (FPOs) were conceived precisely to overcome

these limitations by aggregating farmers into member-owned, professionally managed business entities that can access markets, credit, inputs and technology on more favourable terms than any individual member could negotiate alone.

At the same time, Indian agriculture is undergoing a distinct technological transition. Advances in remote sensing, unmanned aerial vehicles, low-cost sensors, mobile connectivity and artificial intelligence have given rise to a new generation of agri-tech tools: satellite-based crop advisories, drone-based spraying and crop-health mapping, Internet of Things (IoT)-enabled irrigation and soil monitoring, blockchain-based traceability for exports, and app-based platforms for price discovery, input ordering and farm record-keeping. These tools promise significant efficiency gains, but their up-front cost, data requirements and technical complexity make them poorly suited to being adopted farmer by farmer. This chapter argues that FPOs occupy the institutional space needed to close this gap, functioning as an aggregation layer between individual smallholders and the next generation of agricultural technology.

2. Evolution and Institutional Framework of FPOs in India

The producer company form, introduced through an amendment to company law in 2002, gave farmer collectives a hybrid structure combining the mutual-assistance principle of cooperatives with the professional governance and limited liability of a company. Early promotion of FPOs was carried out by agencies such as the Small Farmers' Agri-Business Consortium (SFAC) and the National Bank for Agriculture and Rural Development (NABARD), which supported federations of farmer interest groups into registered producer organizations.

The scale of this effort expanded substantially with the launch of the Central Sector Scheme for the Formation and Promotion of 10,000 FPOs in February 2020, implemented through nine designated implementing agencies, including SFAC, NABARD, the National Cooperative Development Corporation and the National Agricultural Cooperative Marketing Federation. The scheme provides handholding support for five years from formation, matching equity grants, and credit guarantee cover to help new FPOs access institutional finance without collateral. The scheme reached its target of 10,000 registered FPOs during 2025–26, connecting a large number of farmers, a substantial share of them women, into collective enterprises that are now recorded as conducting aggregate business worth thousands of crores of rupees annually. The scheme is being extended for a further five-year cycle from 2026–31 to strengthen governance, working-capital access and market linkage among the FPOs already formed.

This institutional base is significant for the present discussion because it is precisely this network of aggregated farmer enterprises, rather than the individual farm household, that is best positioned to serve as the entry point for next-generation agricultural technology in rural India.

3. The Next-Generation Agri-Tech Landscape

A broad set of technologies is reshaping how agricultural decisions are made and services delivered:

- Precision agriculture and remote sensing: satellite and drone-based imagery for crop-health monitoring, yield estimation and variable-rate input application.
- Internet of Things (IoT) and sensor networks: soil-moisture and weather sensors linked to automated or advisory-based irrigation and nutrient scheduling.
- Artificial intelligence and advisory platforms: mobile applications that combine weather, soil and market data to generate crop-specific, location-specific advisories and pest or disease diagnosis from images.
- Digital marketing and price-discovery platforms: electronic trading platforms and mobile marketplaces that widen buyer access and improve price transparency.
- Agri-fintech and blockchain-based traceability: digital credit scoring based on farm records, and traceability systems that support quality certification and export market access.

Each of these technologies carries a common set of adoption barriers at the level of the individual smallholder: capital cost, minimum scale of operation needed to justify the investment, the technical skill needed for interpretation, and the trust needed to act on a machine-generated recommendation. It is at exactly this point that the FPO structure becomes relevant.

4. FPOs as an Institutional Bridge: Mechanisms

4.1 Aggregation and Shared Investment

An FPO can purchase or lease equipment, such as drones for spraying, soil-testing kits, or farm-machinery banks, that would be unaffordable for an individual smallholder, and make this equipment available to members on a custom-hiring or fee-for-service basis. This model converts a large one-time capital cost into a small, predictable, per-acre service charge for the member farmer, while allowing the equipment to be used at a scale that justifies its purchase.

4.2 Digital and Technical Capacity Building

FPOs, often supported by Cluster-Based Business Organizations, extension agencies and Krishi Vigyan Kendras, provide the training needed for members to understand and trust new tools, ranging from reading a drone-generated crop-health map to using a mobile application for input ordering or produce sale. Board members and paid FPO staff frequently act as local digital champions, translating technical outputs into locally relevant farming decisions for members who may have limited digital literacy.

4.3 Aggregated Data and Customized Advisory

Data-driven advisory services depend on having enough farm records, whether soil-test results, cropping patterns or historical yields, to generate meaningful and locally calibrated

recommendations. An FPO that consolidates member data across a cluster of villages gives agri-tech providers the scale of ground-truthed information needed to make remote-sensing or AI-based advisories more accurate for that specific area, which in turn increases the value delivered back to each member.

4.4 Access to Institutional Credit, Insurance and Digital Records

Because FPOs maintain formal business and membership records, they are better placed than individual smallholders to access the credit guarantee schemes, matching equity grants and working-capital loans that finance technology adoption. Digitized membership and transaction records generated through FPO operations also support parametric crop insurance and alternative credit-scoring models that would otherwise be difficult to construct for farmers without a formal financial history.

4.5 Partnerships with Agri-Tech Enterprises and Start-ups

For agri-tech and agri-input companies, negotiating and servicing thousands of dispersed smallholders individually is commercially unattractive. An FPO with an assured membership base and consolidated demand offers a single point of contact through which start-ups and larger agribusinesses can distribute inputs, extend digital advisory subscriptions, or source produce under contract, at a transaction cost that makes rural, smallholder-dominated markets commercially viable to serve.

5. Illustrative Field Experience

Government reporting on the FPO scheme cites examples of clusters that have used collective structures to move into higher-value, technology-linked production. Vegetable-export clusters around Varanasi expanded cultivated area many-fold over four years with FPO-facilitated market and input linkages, while a fig-producing FPO near Pune secured recognition at a national trade fair and export orders to the European Union on the strength of quality and traceability standards achieved through collective processing. These examples, while specific to particular crops and regions, illustrate a general pattern: technology and market upgrading in Indian smallholder agriculture is occurring through the collective, not the individual, unit of production.

Within extension practice at the district level, FPOs are increasingly used as the platform for organizing front-line demonstrations of drone-based spraying, custom-hiring of farm machinery, soil-health-card-based nutrient management, and digital record-keeping applications, rather than approaching farmers on an individual basis. These concentrates limited extension resources on a manageable number of institutional contact points while still reaching a large number of member farmers through the FPO's own outreach.

6. Role of Krishi Vigyan Kendras and Public Extension

Krishi Vigyan Kendras function as the technical backbone that complements the business orientation of FPOs. While Cluster-Based Business Organizations and implementing agencies

handle registration, governance and financial handholding, KVKs and line-department extension functionaries provide the technology validation, on-farm demonstration and skill training that make new tools credible to farmer members. Capacity-building of FPO Chief Executive Officers and Boards of Directors, joint organization of farmer field schools around precision-agriculture and mechanization themes, and calibration of digital advisories to local agro-climatic conditions are among the extension functions that determine whether a technology introduced through an FPO is actually adopted and sustained by its members.

7. Challenges and Constraints

- Limited managerial and technical capacity within many newly formed FPOs, particularly those still within their initial handholding period.
- Uneven rural connectivity and smartphone penetration, which restrict the reach of app-based and data-intensive advisory tools in several regions.
- Working-capital constraints that limit the ability of FPOs to make the initial investment in shared equipment or digital subscriptions even where matching grants are available.
- Governance and trust issues, including uneven member participation and, in some FPOs, weak accountability of management to the general body.
- Data-privacy and data-ownership questions that arise as FPOs and their technology partners begin to hold increasingly detailed farm-level records.

8. Way Forward

- Convergence between the FPO promotion scheme and public extension infrastructure, so that every FPO formed is linked to its local KVK for technology validation and skill training.
- Continued strengthening of working-capital and equity support to newly formed FPOs, recognizing that technology adoption typically requires investment beyond the initial handholding period.
- Structured public–private partnerships that give agri-tech start-ups a transparent channel to reach FPOs, subject to safeguards on data ownership and pricing.
- Targeted digital-literacy and e-governance training for FPO Boards and staff, so that the institutional bridge itself is technically competent to absorb new tools.
- Monitoring frameworks that track technology adoption and its impact on member income, not only FPO formation and turnover, as an indicator of scheme success.

Conclusion

The dispersed, small-holding structure of Indian agriculture makes individual, farmer-by-farmer adoption of next-generation agri-tech difficult to achieve at scale. Farmer Producer Organizations, built up rapidly over the past several years through a dedicated national scheme,

provide the aggregation, shared investment capacity, data pooling and market linkage that such technologies require to be viable and affordable for smallholders. Strengthening the technical and managerial capacity of FPOs, and deepening their convergence with the public extension system represented by Krishi Vigyan Kendras, is likely to be central to ensuring that the benefits of precision agriculture, digital advisory and agri-fintech innovation reach the smallholder farmers who form the majority of India's farming community.

References

1. Cabinet Committee on Economic Affairs. (2019). *CCEA approves scheme for “Formation and promotion of 10,000 Farmer Producer Organizations (FPOs).”* Press Information Bureau, Government of India.
2. Ministry of Agriculture and Farmers Welfare. (2025). *10,000 FPOs achieved under government's flagship scheme.* Press Information Bureau, Government of India.
3. Ministry of Agriculture and Farmers Welfare. (2026). *Formation and promotion of 10,000 FPOs scheme: Status note presented in the Lok Sabha.* Government of India.
4. Chaturvedi, D. (2025). *Address at the CII FPO Summit on extension of the Central Sector Scheme for FPOs, 2026–31* [Conference proceedings]. Confederation of Indian Industry.
5. Small Farmers' Agri-Business Consortium. (2024). *Guidelines for formation and promotion of Farmer Producer Organizations.* Ministry of Agriculture and Farmers Welfare, Government of India.
6. National Bank for Agriculture and Rural Development. (2024). *Producer organisations development fund: Annual progress report.* NABARD.
7. Trebbin, A., & Hassler, M. (2012). Farmers' producer companies in India: A new concept for collective action? *Environment and Planning A*, 44(2), 411–427.
8. Government of India, Ministry of Agriculture and Farmers Welfare. (2024). *Digital agriculture mission: Framework and implementation guidelines.* Department of Agriculture and Farmers Welfare.

FUTURE-READY AGRICULTURE: TECHNOLOGY, INNOVATION AND RESILIENT FARMING

Arulmozhi R.* and Thendral V.

PG and Research in Department of Microbiology,
Sengamala Thayaar Educational Trust Women's College (Autonomous),
Sundarakkottai, Mannargudi – 614 016, Thiruvavarur district, Tamil Nadu

*Corresponding author E-mail: amozhi72@gmail.com

Abstract

Agriculture is undergoing a major transformation driven by technological advancement, digitalization, biotechnology, climate-smart practices, and data-based decision-making. Increasing population, climate variability, water scarcity, soil degradation, biodiversity decline, emerging pests and diseases, and changing market conditions are placing unprecedented pressure on agricultural production systems. In this context, future-ready agriculture represents an integrated approach that combines scientific knowledge, digital technologies, ecological principles, and innovative farming practices to establish productive, sustainable, inclusive, and resilient agrifood systems. Technologies such as artificial intelligence (AI), machine learning, Internet of Things (IoT)-based sensors, remote sensing, drones, robotics, precision agriculture, geographic information systems (GIS), biotechnology, smart irrigation systems, renewable energy, and digital marketplaces can improve farm management, resource-use efficiency, and decision-making. At the same time, agricultural resilience requires practices that enable farming communities to anticipate, withstand, adapt to, and recover from climatic, biological, economic, and social disturbances. Climate-smart agriculture, conservation agriculture, crop diversification, integrated pest management, soil-health management, water conservation, agroforestry, and circular bioeconomy approaches can complement emerging technologies. Nevertheless, technological transformation is constrained by high initial investment, inadequate digital infrastructure, limited technical skills, concerns regarding data ownership and privacy, unequal access to technology, fragmented landholdings, and insufficient institutional support. Therefore, future-ready agriculture should not be regarded simply as the replacement of traditional farming with advanced machinery or artificial intelligence.

Keywords: Artificial Intelligence, Digital Agriculture, Precision Agriculture, Climate-Smart Agriculture, Agricultural Innovation, Resilient Farming, Biotechnology, Smart Irrigation.

Introduction

Agriculture has historically been a fundamental component of human civilization, providing food, feed, fibre, employment, industrial raw materials, and livelihoods to billions of people.

Despite its importance, the agricultural sector is increasingly exposed to a combination of environmental, climatic, technological, economic, and social challenges. Climate variability, extreme weather events, declining soil fertility, water scarcity, land degradation, biodiversity loss, emerging pests and diseases, and increasing production costs have created considerable uncertainty for farmers and agricultural communities.

These challenges demonstrate the need to move beyond conventional productivity-oriented agricultural models toward systems that can simultaneously maintain productivity, conserve natural resources, protect ecosystems, and withstand disturbances. Transformation is required throughout the agrifood system, including production, input supply, processing, storage, transportation, distribution, consumption, and waste management.

Future-ready agriculture represents an important pathway toward this transformation. It integrates traditional agricultural knowledge with digital technologies, biological sciences, engineering, renewable energy, ecological principles, and data-driven management. In this approach, technology is not treated as an independent solution but as a tool that can be adapted to local environmental, socioeconomic, and agricultural conditions.

The primary objective of future-ready agriculture is therefore not simply to increase food production. It is to produce sufficient and nutritious food efficiently while conserving soil, water, biodiversity, and energy, improving farmer livelihoods, and strengthening the capacity of agricultural systems to respond to future uncertainties. Such an approach is consistent with the broader need for sustainable and resilient agrifood systems (Food and Agriculture Organization of the United Nations FAO, 2024; Intergovernmental Panel on Climate Change IPCC, 2023).

Concept of Future-Ready Agriculture

Future-ready agriculture can be described as an agricultural production and food-system approach that integrates scientific knowledge, emerging technologies, sustainable resource-management practices, and adaptive strategies to prepare farming systems for future environmental, economic, climatic, and social challenges.

A future-ready agricultural system is based on five closely connected dimensions:

- 1. Technological readiness** – adoption of appropriate digital, biological, engineering, and automation technologies.
- 2. Environmental sustainability** – responsible management of soil, water, biodiversity, energy, and other natural resources.
- 3. Climate resilience** – capacity to anticipate, withstand, adapt to, and recover from climatic disturbances.
- 4. Economic viability** – improvement of farm profitability, market access, value addition, and financial security.

- 5. Social inclusiveness** – ensuring that technologies and innovations are accessible to smallholders, women, youth, and other farming communities.

These dimensions should function collectively rather than as separate components. Digital tools, for example, may improve resource management, but their effectiveness depends on farmer knowledge, infrastructure, affordability, and institutional support. Similarly, ecological farming practices can strengthen resilience but may benefit from appropriate technologies for monitoring and decision-making.

Drivers of Agricultural Transformation

Several interacting forces are accelerating the transformation of agriculture. Climate change is influencing temperature regimes, rainfall patterns, pest and disease dynamics, water availability, and crop productivity. Population growth and changes in dietary preferences are increasing demand for food and agricultural commodities. At the same time, declining availability of freshwater, fertile soil, and productive land is placing greater pressure on natural resources.

Labour shortages and rising labour costs are encouraging mechanization, automation, and robotics. Increasing market volatility has strengthened the need for timely information related to prices, demand, storage, transportation, and value addition. Digital platforms can provide farmers with access to market information, financial services, weather advisories, technical knowledge, and potential buyers.

These drivers indicate that agricultural transformation involves much more than technological modernization. It requires changes in production practices, resource management, knowledge systems, markets, institutions, and farmer participation.

Emerging Technologies in Future Agriculture

Technological innovation is becoming increasingly important in agricultural decision-making and farm management. Artificial intelligence and machine learning can assist with crop disease identification, yield forecasting, weed detection, irrigation scheduling, weather analysis, pest prediction, and market intelligence. When appropriately developed and validated, these tools can process large quantities of information and support timely decisions.

The Internet of Things enables connected sensors and devices to collect information on soil moisture, temperature, humidity, nutrient status, water levels, and crop conditions. Such real-time information can assist farmers in determining when irrigation, fertilization, or other interventions are required.

Remote sensing and satellite imagery provide information about crop growth, vegetation health, land use, soil conditions, and environmental changes over large areas. Drones can complement satellite observations by providing high-resolution information at the field level. They can be used for crop monitoring, disease and weed identification, plant health assessment, and targeted farm operations.

Robotics and automated machinery are also being developed for activities such as planting, weeding, harvesting, milking, crop monitoring, and material handling. These technologies may reduce labour requirements and improve operational precision.

However, the effectiveness of emerging agricultural technologies depends on the quality of available data, local validation, affordability, connectivity, maintenance, and farmer skills. Consequently, technological systems should complement farmers' experience and knowledge rather than attempt to eliminate the human role in agricultural decision-making (Klerkx *et al.*, 2019; Liakos *et al.*, 2018).

Precision Agriculture

Precision agriculture is an approach that uses spatial and temporal information to manage agricultural resources according to the specific requirements of crops and field locations. Major components include global positioning systems, geographic information systems, remote sensing, sensors, yield monitors, variable-rate application technologies, and digital decision-support systems. Agricultural fields are rarely uniform. Soil fertility, moisture, nutrient availability, crop growth, weed infestation, and pest pressure may vary considerably within the same field. Precision agriculture seeks to identify these variations and apply inputs according to site-specific requirements. Appropriate precision-management strategies can improve the efficiency of water, fertilizers, pesticides, seeds, and energy. They may also reduce unnecessary input application and associated environmental impacts. The application of precision agriculture therefore links technological innovation with resource conservation and sustainable intensification (Gebbers and Adamchuk, 2010; Mulla, 2013).

Digital Agriculture and Data-Driven Farming

Digital agriculture extends beyond individual farm technologies and incorporates digital tools throughout the agricultural value chain. Mobile applications, online platforms, cloud-based systems, digital advisory services, and data-management tools can connect farmers with weather information, agricultural experts, input suppliers, financial institutions, government programmes, consumers, and markets. Digital traceability systems can improve transparency in agricultural supply chains by recording information related to production, processing, transportation, and distribution. Digital marketplaces may provide farmers with opportunities to identify buyers and access market information more efficiently.

However, the expansion of digital agriculture also creates important concerns. Data ownership, privacy, cybersecurity, interoperability, data quality, and unequal access must be addressed. Farmers should have appropriate control over information generated through their farming activities. Digital transformation should therefore be accompanied by suitable governance frameworks, digital literacy programmes, affordable connectivity, and institutional support (World Bank, 2019, 2021).

Biotechnology and Biological Innovation

Biotechnology provides multiple opportunities for improving agricultural productivity, resource efficiency, and resilience. Important applications include improved crop varieties, tissue culture, microbial technologies, molecular diagnostics, biological control, and advanced genetic technologies. Beneficial microorganisms such as nitrogen-fixing bacteria, phosphate-solubilizing microorganisms, arbuscular mycorrhizal fungi, and plant-growth-promoting rhizobacteria can contribute to nutrient availability, plant growth, soil biological activity, and crop health. Microbial biofertilizers and biocontrol agents can therefore complement chemical inputs and support more sustainable agricultural systems.

Biological control is also an important component of integrated pest management. Beneficial microorganisms and natural enemies can help suppress agricultural pests and diseases while reducing excessive dependence on chemical pesticides.

Modern molecular and genetic technologies may accelerate the development of crops with desirable characteristics, including tolerance to drought, salinity, heat, pests, and diseases. However, such technologies require appropriate biosafety assessment, regulatory oversight, risk evaluation, and ecological monitoring. Responsible innovation is therefore essential when introducing advanced biological technologies into agricultural systems.

Climate-Smart and Resilient Farming

Agricultural resilience refers to the capacity of farming systems and communities to prepare for, withstand, adapt to, and recover from environmental, climatic, biological, economic, and social disturbances. Climate-resilient agriculture combines technological innovation with ecological management and locally appropriate agricultural practices.

Crop diversification, intercropping, crop rotation, climate-resilient varieties, conservation agriculture, agroforestry, integrated farming systems, and improved water management can reduce agricultural vulnerability. Diversification can reduce dependence on a single crop and may provide alternative sources of income and food during periods of environmental stress.

Conservation agriculture generally emphasizes three interconnected principles: minimum soil disturbance, maintenance of soil cover, and crop diversification. These practices can contribute to soil conservation and improved resource management when adapted to local conditions.

Agroforestry integrates trees with crops and/or livestock and can provide ecological and economic benefits, including improved biodiversity, soil protection, microclimate regulation, biomass production, and diversified farm income. The effectiveness of such practices depends on climatic conditions, crop combinations, management systems, and local socioeconomic circumstances (IPCC, 2022).

Smart Water Management

Water is among the most important and increasingly constrained resources in agriculture. Efficient water management is therefore central to future-ready farming.

Smart irrigation systems can integrate soil-moisture sensors, weather information, automated valves, irrigation controllers, and crop water-demand models to deliver water according to actual crop requirements. Such systems can help reduce unnecessary irrigation and improve water-use efficiency. Other important water-management practices include drip irrigation, rainwater harvesting, mulching, water-efficient crop varieties, farm ponds, watershed management, and improved soil-water conservation.

However, farm-level irrigation efficiency alone does not necessarily guarantee sustainable water use at the watershed scale. If increased efficiency encourages expansion of irrigated areas or additional water extraction, groundwater and surface-water resources may continue to decline. Consequently, future water management should integrate farm-level efficiency with watershed-level planning, groundwater governance, and community participation.

Soil Health and Regenerative Approaches

Healthy soil is fundamental to sustainable agricultural productivity. Soil degradation may result from erosion, excessive tillage, nutrient imbalance, salinity, compaction, loss of organic matter, and inappropriate land-management practices.

Future-ready agriculture should therefore incorporate systematic soil-health monitoring and management. Important practices include organic-matter addition, compost application, cover cropping, crop rotation, reduced tillage, integrated nutrient management, biofertilizer use, mulching, and appropriate residue management. Regenerative agricultural approaches place particular emphasis on restoring soil biological activity, improving soil structure, increasing organic matter, and strengthening ecological functions while maintaining agricultural productivity. Nevertheless, the outcomes of regenerative practices can vary according to soil type, climate, crop species, farm management, and local conditions. Therefore, practices should be evaluated and validated under region-specific circumstances rather than assumed to produce identical outcomes everywhere (Pretty & Bharucha, 2014; Pretty *et al.*, 2018).

Renewable Energy and Circular Agriculture

Renewable energy can contribute to reducing dependence on fossil fuels in agricultural operations. Solar-powered irrigation systems, solar dryers, biogas plants, biomass-energy systems, and renewable-energy-supported cold storage are examples of potential applications.

Circular agriculture aims to reduce waste and maximize the recovery and reuse of nutrients, biomass, water, and energy. Crop residues can potentially be converted into compost, biochar, animal feed, or bioenergy depending on their characteristics, local requirements, and safety considerations. Animal manure can be processed into compost, biogas, or organic fertilizers. Food-processing residues may be utilized for animal feed, composting, bioenergy generation, or other value-added applications. Such approaches can contribute to resource efficiency and waste reduction while potentially generating additional economic value.

Smart Greenhouses and Controlled-Environment Agriculture

Controlled-environment agriculture includes greenhouse production, vertical farming, hydroponics, aeroponics, and related systems in which environmental conditions are actively managed. Temperature, humidity, light, irrigation, carbon dioxide concentration, and nutrient supply can be monitored and regulated to support crop production.

Such systems can improve water-use efficiency and allow production under conditions where conventional farming may be difficult. They may also provide greater control over environmental factors and facilitate year-round production for selected crops.

However, controlled-environment systems can require substantial capital investment, energy, infrastructure, and technical expertise. Their overall sustainability therefore depends on system design, energy sources, crop selection, water use, local climatic conditions, and economic feasibility. Controlled-environment agriculture should consequently be considered as one component of agricultural diversification rather than a universal replacement for open-field farming.

Digital Early-Warning Systems and Disaster Resilience

Agricultural resilience depends partly on the ability to identify potential hazards before they cause severe damage. Satellite observations, weather forecasting, artificial intelligence, mobile communication systems, pest surveillance, and digital advisory platforms can contribute to early-warning mechanisms for droughts, floods, pest outbreaks, diseases, and other agricultural risks.

An effective agricultural early-warning system can be represented by the following sequence:

Observation → Analysis → Risk Assessment → Advisory → Farmer Action → Monitoring

The usefulness of an early-warning system depends not only on the accuracy of its predictions but also on whether the information reaches farmers in sufficient time and can be converted into practical decisions. Local-language communication, accessible advisory services, extension support, and farmer participation are therefore important components of effective agricultural risk management.

Challenges in Future-Ready Agriculture

Despite the potential benefits of technological transformation, several barriers can restrict the adoption of future-ready agricultural practices.

Major challenges include:

- High initial investment requirements.
- Limited rural digital infrastructure.
- Poor internet and electricity connectivity in some regions.
- Insufficient technical and digital skills.
- Limited access to maintenance and technical support.
- Concerns regarding data ownership and privacy.

- Lack of interoperability between digital platforms.
- Fragmented agricultural landholdings.
- Limited access to institutional finance.
- Unequal access to technologies.
- Uncertainty regarding the suitability of technologies under local conditions.
- Possible changes in rural employment patterns resulting from automation.

Addressing these challenges requires coordinated interventions involving farmer training, agricultural extension, affordable financial mechanisms, infrastructure development, technology demonstration, institutional support, and inclusive public policies. Technology adoption should be evaluated not only in terms of technical performance but also according to affordability, accessibility, environmental consequences, and socioeconomic outcomes.

Role of Farmers, Extension Services and Institutions

Farmers should be active participants in agricultural innovation rather than passive recipients of technologies. Participatory research, farmer field demonstrations, on-farm experimentation, digital learning platforms, and community-based innovation can improve the suitability and adoption of new technologies. Agricultural universities and research institutions have important roles in technology development, field validation, crop improvement, soil and water research, microbial innovation, pest and disease surveillance, and farmer training. Extension systems can combine conventional face-to-face approaches with digital advisory services. Mobile-based advisories, online training, digital crop-monitoring systems, and localized weather information can extend the reach of agricultural knowledge.

Governments and institutional organizations can facilitate transformation through rural connectivity, agricultural research funding, digital infrastructure, extension services, agricultural credit, insurance mechanisms, market infrastructure, digital literacy, and policies that promote equitable access to innovation.

Future Directions

The future of agriculture is likely to be characterized by increasing integration among multiple technologies rather than the isolated use of individual tools. A future farm may combine satellite imagery, IoT sensors, artificial intelligence, weather forecasting, automated irrigation, robotics, biological inputs, and digital market platforms within a single management framework.

Potential future developments include:

- AI-based agricultural advisory systems.
- Autonomous and semi-autonomous agricultural machinery.
- Advanced microbial and biological inputs.
- Climate-resilient crop varieties.

- Predictive models for pest and disease outbreaks.
- Automated and sensor-based irrigation systems.
- Smart greenhouse and controlled-environment technologies.
- Digital traceability throughout agricultural supply chains.
- Renewable-energy-supported agricultural operations.
- Digital financial and insurance services.
- Integrated soil-health and biodiversity monitoring.

The value of these innovations will ultimately depend on their ability to address real agricultural problems while remaining affordable, adaptable, environmentally responsible, and accessible to farming communities. Future agricultural technologies should therefore be developed through collaboration among farmers, scientists, engineers, policymakers, extension professionals, technology developers, and other stakeholders.

Conclusion

Future-ready agriculture represents a transition toward agricultural systems that are technologically capable, environmentally sustainable, economically viable, socially inclusive, and resilient to future uncertainties. Artificial intelligence, IoT, remote sensing, drones, robotics, precision agriculture, biotechnology, and digital marketplaces provide important opportunities to improve agricultural decision-making, productivity, and resource-use efficiency.

At the same time, technological innovation alone cannot provide a complete solution to the challenges facing agriculture. Climate-smart farming, crop diversification, conservation agriculture, agroforestry, soil-health management, water conservation, integrated pest management, and circular resource-use practices remain essential for maintaining ecological resilience.

Successful digital and technological transformation also requires reliable infrastructure, appropriate policies, farmer training, effective extension systems, responsible data governance, affordable financing, and equitable access to technology. Smallholder farmers should remain central participants in agricultural innovation and should have opportunities to evaluate and adapt technologies according to their own farming conditions.

The agriculture of the future should therefore emerge from the integration of modern science, digital innovation, ecological principles, indigenous knowledge, and farmers' practical experience. A balanced approach that combines technological progress with sustainability and social inclusion can strengthen the capacity of agrifood systems to address future challenges related to food security, climate change, natural-resource conservation, and rural livelihoods.

Table 1: Major dimensions of future-ready agriculture

Dimension	Major Approaches	Expected Contribution
Digital agriculture	AI, IoT, mobile applications, cloud computing	Improved decision-making and farm management
Precision agriculture	GPS, sensors, remote sensing, variable-rate technologies	More efficient use of agricultural inputs
Climate resilience	Climate-resilient crops, diversification, water conservation	Reduced vulnerability to climate-related stresses
Biotechnology	Improved varieties, microbial products, molecular and genetic technologies	Productivity enhancement and stress tolerance
Automation	Robotics, drones, autonomous machinery	Improved operational efficiency and reduced labour requirements
Circular agriculture	Biomass, nutrient and waste recycling	Reduced agricultural waste and improved resource recovery
Renewable energy	Solar pumps, solar dryers, biogas and biomass systems	Reduced dependence on fossil fuels
Digital markets	E-commerce and digital agricultural platforms	Improved market information and connectivity

Table 2: Digital technologies and their agricultural applications

Technology	Agricultural Application
Artificial intelligence	Disease diagnosis, yield prediction, pest forecasting and decision support
Internet of Things	Real-time monitoring of soil, crops, water and environmental conditions
Drones	Crop surveillance, field mapping and targeted crop-management operations
Satellite remote sensing	Large-scale crop monitoring and environmental assessment
Geographic Information Systems	Spatial analysis, field mapping and resource planning
Mobile applications	Agricultural advisory, weather information and market access
Cloud computing	Data storage, processing and analytical services
Blockchain	Agricultural supply-chain traceability and information management
Robotics	Automated planting, weeding, harvesting and monitoring

Table 3: Circular Approaches in Agriculture

Waste/Resource	Possible Circular Pathway
Crop residues	Compost, biochar, animal feed or biomass energy
Animal manure	Biogas, compost and organic fertilizer
Food-processing residues	Animal feed, compost, bioenergy and value-added products
Wastewater	Appropriate treatment and reuse where safe and permitted
Organic wastes	Nutrient recovery, composting and biological processing

References

1. Food and Agriculture Organization of the United Nations. (2022a). *Digital agriculture in action: Artificial intelligence for agriculture*. FAO.
2. Food and Agriculture Organization of the United Nations. (2022b). *Transforming food systems in India with digital agriculture*. FAO Investment Centre.
3. Food and Agriculture Organization of the United Nations. (2024a). *Climate technologies for agrifood systems transformation*. FAO.
4. Food and Agriculture Organization of the United Nations. (2024b). *The role of innovation and digitalization in the sustainable use of natural resources to accelerate the implementation of climate-resilient and low-emission pathways in agrifood systems*. FAO Regional Office for Europe and Central Asia.
5. Food and Agriculture Organization of the United Nations. (2024c). *The state of food and agriculture 2024: Value-driven transformation of agrifood systems*. FAO.
6. Food and Agriculture Organization of the United Nations. (2025). *Digital agriculture and AI innovation roadmap*. FAO.
7. Gebbers, R., & Adamchuk, V. I. (2010). Precision agriculture and food security. *Science*, 327(5967), 828–831. <https://doi.org/10.1126/science.1183899>
8. Intergovernmental Panel on Climate Change. (2022). *Climate change 2022: Impacts, adaptation and vulnerability*. Cambridge University Press. <https://doi.org/10.1017/9781009325844>
9. Intergovernmental Panel on Climate Change. (2023). *Climate change 2023: Synthesis report*. IPCC.
10. Klerkx, L., Jakku, E., & Labarthe, P. (2019). A review of social science on digital agriculture, smart farming and agriculture 4.0: New contributions and a future research agenda. *NJAS: Wageningen Journal of Life Sciences*, 90–91, 100315. <https://doi.org/10.1016/j.njas.2019.100315>
11. Liakos, K. G., Busato, P., Moshou, D., Pearson, S., & Bochtis, D. (2018). Machine learning in agriculture: A review. *Sensors*, 18(8), 2674. <https://doi.org/10.3390/s18082674>

12. Mulla, D. J. (2013). Twenty five years of remote sensing in precision agriculture: Key advances and remaining knowledge gaps. *Biosystems Engineering*, 114(4), 358–371. <https://doi.org/10.1016/j.biosystemseng.2012.08.009>
13. Pretty, J., & Bharucha, Z. P. (2014). Sustainable intensification in agricultural systems. *Annals of Botany*, 114(8), 1571–1596. <https://doi.org/10.1093/aob/mcu205>
14. Pretty, J., Benton, T. G., Bharucha, Z. P., Dicks, L. V., Flora, C. B., Godfray, H. C. J., Goulson, D., Hartley, S., Lampkin, N., Morris, C., Pierzynski, G., Prasad, P. V. V., Reganold, J., Rockström, J., Smith, P., Thorne, P., & Wratten, S. (2018). Global assessment of agricultural system redesign for sustainable intensification. *Nature Sustainability*, 1, 441–446. <https://doi.org/10.1038/s41893-018-0114-0>
15. Rockström, J., Williams, J., Daily, G., Noble, A., Matthews, N., Gordon, L., Wetterstrand, H., DeClerck, F., Shah, M., Steduto, P., de Fraiture, C., Hatibu, N., Unver, O., Bird, J., Sibanda, L., & Smith, J. (2017). Sustainable intensification of agriculture for human prosperity and global sustainability. *Ambio*, 46, 4–17. <https://doi.org/10.1007/s13280-016-0793-6>
16. United Nations. (2015). *Transforming our world: The 2030 agenda for sustainable development*. United Nations.
17. Wolfert, S., Ge, L., Verdouw, C., & Bogaardt, M.-J. (2017). Big data in smart farming—A review. *Agricultural Systems*, 153, 69–80. <https://doi.org/10.1016/j.agsy.2017.01.015>
18. World Bank. (2019). *Future of food: Harnessing digital technologies to improve food system outcomes*. World Bank.
19. World Bank. (2021). *What's cooking? Digital transformation of the agrifood system*. World Bank.
20. World Bank. (2026). *Small AI transforms farming in India*. World Bank.

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About Editors



Dr. Rakesh Kumar is an Assistant Professor in the Department of Mechanical Engineering at Guru Jambheshwar University of Science & Technology (GJUS&T), Hisar, Haryana, India, with 12 years of teaching and academic experience. His research interests include thermal engineering, energy and exergy analysis, heat transfer, sustainable energy technologies, jaggery manufacturing, and agro-processing systems. He has published research and review articles in reputed journals and conference proceedings, with over 400 citations, an h-index of 10, and an i10-index of 12. He has supervised around 10 M.Tech. students and is currently supervising one Ph.D. scholar. His research focuses on innovative, energy-efficient, and environmentally sustainable technologies for agro-industrial applications. He has contributed to research projects, technology development, scholarly publications, and academic activities. His work demonstrates a strong commitment to advancing sustainable technologies through research, innovation, experimentation, and practical engineering applications in agro-industrial sectors.



Prof. (Dr.) Suryakant Vishwas Maske is a Professor of Zoology at Shri Vijaysinha Yadau College, Peth Vadgaon, District Kolhapur, Maharashtra. He serves as a member of the Board of Studies for two universities and one autonomous college. With 25 years of teaching and research experience, he has made significant contributions to zoological education and research. He has authored three reference books and contributed three book chapters at the international level. His research work includes 30 papers published in reputed national and international journals. He has also contributed to three Indian patents, reflecting his interest in innovative research and scientific applications. In recognition of his academic excellence and professional contributions, he has received six prestigious awards. His extensive experience and scholarly contributions have enriched the field of Zoology.



Dr. Aashish Dhull is a veterinary professional with an MVSc in Animal Reproduction, Gynaecology and Obstetrics (ARGO). He is currently working as an Assistant Professor at a private veterinary college, contributing to veterinary education and academic development. He qualified the ICAR-NET and ARS Preliminary examinations in his first attempt, demonstrating strong academic proficiency and subject expertise. He was also awarded the ICAR-PG Scholarship (ICAR-JRF) for postgraduate studies. His academic and professional interests encompass veterinary reproduction, animal health, and allied sciences. He has contributed to research publications and book chapters, reflecting his engagement in scholarly activities. He has also participated in academic training programmes in veterinary and allied sciences.



Dr. S. Subramanian is an Assistant Professor in the Department of Nautical Science at AMET University, Chennai. He earned his Ph.D. in Remote Sensing from Gandhigram Rural Institute, Dindigul, Tamil Nadu, in 2025, and holds an M.Sc. in Geology from the University of Madras. His expertise includes Geology, Geoinformatics, and Remote Sensing. He has four years of teaching experience and two decades of experience in Oil & Gas and Mining, with exposure in Asia and Africa. He has contributed publications, book chapters, papers on geospatial technologies, groundwater management, mining, and sustainable development. His research focuses on Remote Sensing and GIS for mineral exploration, groundwater assessment, environmental monitoring, and sustainable development. He has received the NPTEL Discipline Star and Best Faculty Awards.

