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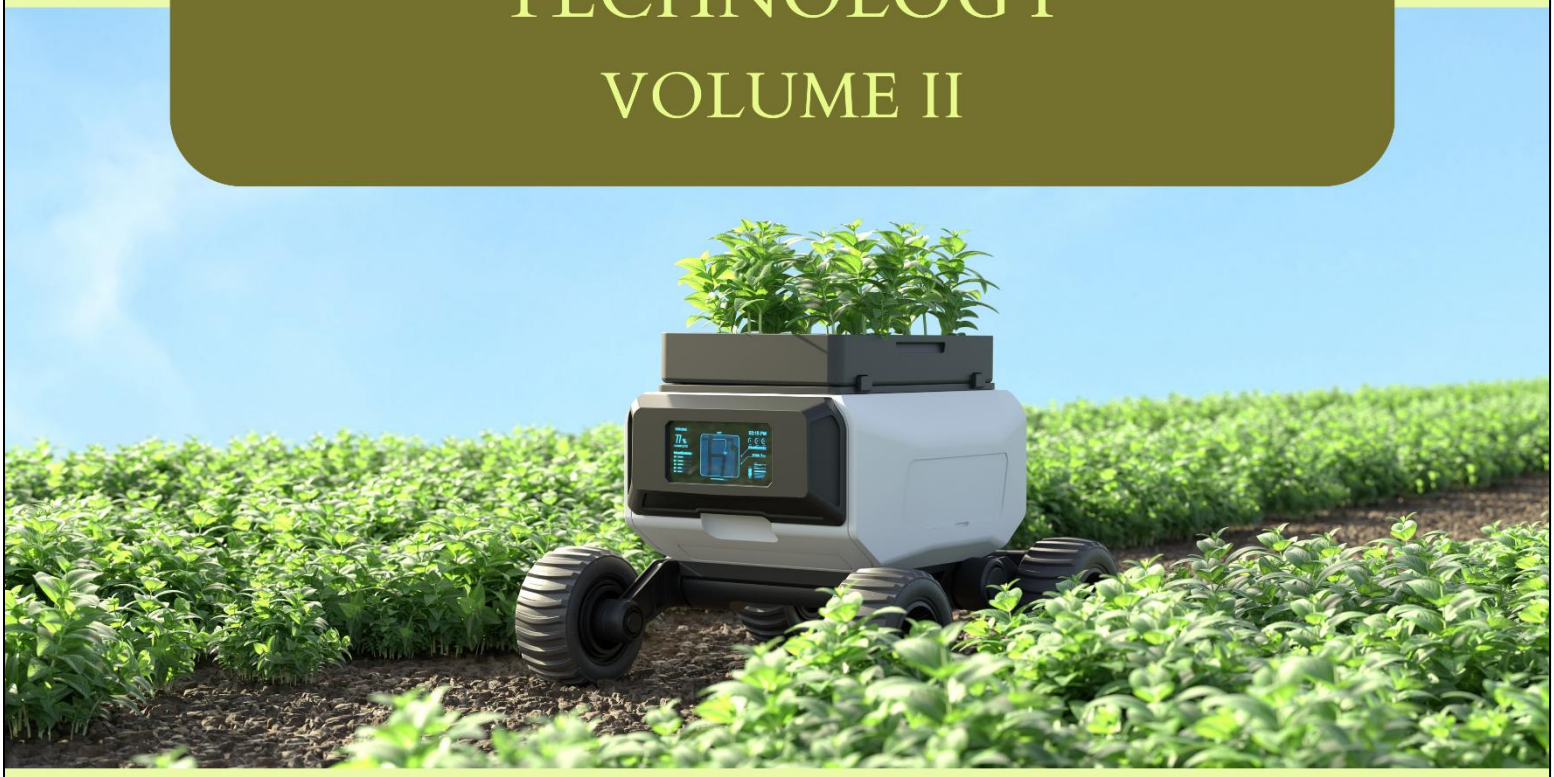

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Smart Agriculture: Policy, Practice and Technology Volume II

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PREFACE

Agriculture has always been the backbone of human civilization, sustaining economies, livelihoods, and food security across the globe. In the twenty-first century, however, agriculture faces unprecedented challenges arising from climate change, declining natural resources, population growth, biodiversity loss, and increasing demands for sustainable food production. These challenges necessitate innovative approaches that integrate scientific advancement with practical farming systems. In this context, smart agriculture has emerged as a transformative paradigm that combines policy support, modern technologies, and sustainable agricultural practices to improve productivity, efficiency, and resilience.

The book *Smart Agriculture: Policy, Practice and Technology* aim to provide a comprehensive understanding of the rapidly evolving landscape of modern agriculture. It explores the integration of digital technologies such as Artificial Intelligence (AI), the Internet of Things (IoT), remote sensing, drones, precision farming, blockchain technology, robotics, and big data analytics in agricultural systems. At the same time, the book emphasizes the importance of farmer-centric policies, climate-resilient practices, resource conservation, and sustainable rural development.

This volume brings together contributions from researchers, academicians, scientists, policymakers, extension workers, and industry experts who have shared their valuable insights and experiences in the field of smart agriculture. The chapters included in this book highlight both theoretical foundations and practical applications, offering readers a multidisciplinary perspective on contemporary agricultural innovations and challenges.

The editors sincerely hope that this book will serve as a valuable resource for students, researchers, teachers, policymakers, agricultural professionals, and progressive farmers. It is intended not only to enrich academic knowledge but also to inspire practical solutions for sustainable agricultural development and food security.

We express our heartfelt gratitude to all contributors, reviewers, and well-wishers whose support and cooperation made this publication possible. We also thank the publishers for their dedication and efforts in bringing this work to fruition.

- Editors

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TRANSFORMING AGRICULTURE THROUGH AI, IOT AND DATA-DRIVEN INNOVATIONS

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Abstract

The convergence of digital technologies with agricultural practice has given rise to what is increasingly called smart agriculture, a paradigm that encompasses precision farming, artificial intelligence, the Internet of Things, remote sensing, blockchain and data analytics in service of more productive, efficient and sustainable food systems. Yet the gap between smart agriculture's technical promise and its practical realisation across diverse farming contexts remains wide, particularly in developing country settings where smallholder farmers carry the heaviest burden of climate vulnerability and food insecurity. This chapter examines smart agriculture across three interconnected analytical dimensions: the technological systems and their documented capabilities; the policy frameworks that enable or constrain adoption; and the on-the-ground practices through which farmers, institutions and markets negotiate the terms of digital agricultural transformation. The chapter is grounded in a systems innovation theoretical framework, drawing on sustainability transitions theory and the multi-level perspective to analyse how smart agriculture technologies emerge, diffuse and encounter resistance across sociotechnical landscapes shaped by institutional inertia, economic inequality and divergent regulatory environments. It advances the argument that smart agriculture is not a neutral technological upgrade of existing farming practice but a sociotechnical transformation whose direction, beneficiaries and risks are determined by policy choices, power relations and institutional arrangements that must be analysed alongside the technical systems themselves. Through an examination of the empirical literature and three comparative case studies drawn from precision agriculture adoption in South Africa, climate-smart agriculture policy implementation in West Africa and blockchain-enabled supply chain transparency in the European agri-food sector, the chapter documents both the genuine agricultural benefits that smart technologies deliver under enabling conditions and the structural barriers that prevent those benefits from reaching the farming communities most in need of them. This chapter argues that realizing the potential of smart agriculture for inclusive and sustainable food system transformation requires policy frameworks addressing infrastructure, finance, digital literacy, and institutional coordination to ensure equitable technological benefits.

Keywords: Blockchain Technology, Smart Agriculture, Policy, Artificial Intelligence.

Introduction

Agriculture is in the middle of what some researchers are calling its fourth revolution. The first revolution brought the plough and settled cultivation. The second brought irrigation and crop diversification. The third brought mechanisation, synthetic inputs and the Green Revolution's high-yielding varieties. The fourth, still in progress, is bringing data. Sensors in the soil, satellites in orbit, drones in the air and artificial intelligence in the cloud are together creating unprecedented capabilities for understanding and managing agricultural systems with a precision, responsiveness and analytical depth that no previous technology has provided. Smart agriculture, as this technological convergence is most commonly called, promises to address simultaneously the productivity demands of a world population projected to reach ten billion by 2050, the climate adaptation requirements of farming systems facing unprecedented environmental disruption and the sustainability imperatives of food systems that currently account for a third of global greenhouse gas emissions.

Miller *et al.* (2025), in their systematic review of IoT and AI in agriculture, confirmed that the integration of these technologies had reshaped modern agriculture by enabling precision farming, real-time monitoring and data-driven decision-making, with research activity in the field accelerating dramatically from 2020 onward, particularly in the years 2022 to 2024, reflecting growing acceptance driven by advances in low-power IoT devices, cloud computing and accessible machine learning tools. The field has matured from early proof-of-concept demonstrations to documented operational deployments delivering measurable productivity gains, with Duguma and Bai (2024) confirming that IoT-based precision agriculture systems could increase crop yields by up to 20 % compared to traditional methods.

Yet this technological momentum is unevenly distributed in ways that reproduce and sometimes amplify existing inequalities in agricultural capacity. The farming systems with the greatest need for the productivity, resilience and efficiency improvements that smart agriculture promises are precisely those in sub-Saharan Africa, South Asia and other developing regions where infrastructure limitations, affordability constraints and institutional gaps make adoption most difficult. Finizola e Silva *et al.* (2024), in their systematic literature review of the drivers and barriers to climate-smart agriculture adoption among African farmers, found that despite widespread attention and support, adoption among African smallholder farmers remained low, with lack of knowledge, insufficient financial resources and fragmented institutional support consistently identified as primary barriers. Understanding why smart agriculture's benefits remain so unevenly distributed and what policy, institutional and technological design choices would produce a more equitable distribution, is the central analytical concern of this chapter.

Literature Review

The Technological Landscape of Smart Agriculture

Smart agriculture encompasses a diverse and rapidly evolving suite of technologies whose common thread is the use of digital data, connectivity and analytical intelligence to improve agricultural decision-making and operational efficiency. The core technological building blocks, the Internet of Things, artificial intelligence and machine learning, remote sensing through satellite and drone platforms, geographic information systems, blockchain and cloud computing, are increasingly being deployed not as isolated tools but as integrated systems whose combined capabilities exceed what any single technology provides.

The Internet of Things provides the data acquisition layer of smart agriculture, through sensors embedded in soil, atmosphere and crop structures that continuously monitor the environmental parameters determining plant growth and health. Miller *et al.* (2025) found that IoT-based sensor networks, when integrated with AI-driven analytics, significantly improved agricultural monitoring and management across the studies reviewed, with the integration of these two technology classes producing outcomes substantially better than either class achieved independently. Soil moisture sensors, temperature and humidity monitors, plant stress sensors, weather stations and livestock health monitors together create data environments of extraordinary granularity and temporal resolution that traditional farm observation could not approach.

Artificial intelligence provides the analytical layer, converting raw sensor data into actionable management recommendations and predictive insights. Mansoor *et al.* (2025) found that smart sensor technologies were foundational to precision farming, providing crucial information regarding soil conditions, plant growth and environmental factors in real time and that when these data streams were processed by machine learning models, the resulting management recommendations reliably outperformed those derived from conventional agronomic expertise alone. Machine learning models including support vector machines, convolutional neural networks and random forests have been successfully applied to crop disease identification, yield prediction, pest outbreak forecasting and irrigation optimisation, demonstrating the breadth of agricultural functions amenable to AI-driven improvement.

Remote sensing from satellite and drone platforms provides the spatial dimension of smart agriculture's data infrastructure, enabling the comprehensive field-level and landscape-level mapping of crop conditions that ground-based sensors alone cannot achieve. Wang *et al.* (2025), examining the evolution of precision agriculture and food safety, confirmed that satellite remote sensing and drone technology could effectively predict crop yields and implement precise fertilisation strategies, with vegetation indices derived from multispectral imagery providing quantitative assessments of crop biomass and health at spatial resolutions sufficient for site-

specific management. The availability of free satellite data from the European Space Agency's Sentinel programme has progressively democratised access to remote sensing-based agricultural intelligence, enabling the development of crop monitoring tools accessible to a wider range of agricultural actors than commercial high-resolution imagery could serve.

Blockchain technology brings a different capability to smart agriculture: the creation of immutable, verifiable records of agricultural transactions, certifications and provenance claims that can be accessed by multiple parties without requiring central institutional authority. Lai *et al.* (2025), developing a governance framework for digital traceability in food supply chains, found that digital traceability systems were emerging as key strategies for improving value creation across agri-food supply chains, with blockchain's capacity to create cryptographically secured, tamper-proof records of product origin, production methods and handling conditions enabling the verification of food safety and sustainability claims that premium markets increasingly demanded. The integration of blockchain with IoT sensing created hybrid systems in which sensor data about production conditions was automatically recorded to an immutable ledger, creating auditable records without the costly and time-consuming manual documentation that conventional certification required.

Policy Frameworks for Smart Agriculture

Smart agricultural technologies do not emerge and diffuse through purely market-driven processes; they are shaped at every stage by the policy environments that determine what technologies are publicly funded for development, what regulatory frameworks govern their deployment, what financial instruments are available to support adoption and what institutional architectures connect technology developers with the farming communities they aim to serve. Understanding the policy landscape of smart agriculture is therefore as important as understanding the technological landscape and the two are inseparably connected in ways that the dominant technology-focused literature on smart agriculture often underappreciates.

The most influential international policy framework shaping smart agriculture development is the climate-smart agriculture agenda, developed by the Food and Agriculture Organisation and endorsed by numerous national governments and international development organisations, which explicitly links agricultural technology development to the triple objectives of productivity improvement, climate adaptation and greenhouse gas emission reduction. Nkosi *et al.* (2025), reviewing the adoption and scaling of climate-smart agriculture innovations among smallholder farmers in South Africa, confirmed that climate-smart agriculture had emerged as a critical strategy to address the intertwined challenges of climate change, food insecurity and environmental degradation, while simultaneously documenting that adoption remained uneven and limited despite substantial policy attention and public investment. The gap between the policy ambition of climate-smart agriculture and the lived experience of smallholder farmers

navigating its adoption was explained by multiple interacting barriers including insecure land tenure, insufficient extension services, limited credit access and fragmented institutional support.

National agricultural digitalisation policies vary substantially in ambition, coherence and implementation effectiveness across the global landscape. The European Union has pursued one of the most comprehensive approaches to smart agriculture governance, combining the Common Agricultural Policy's investment support for farm technology adoption with the Farm to Fork Strategy's sustainability objectives and the Digital Europe Programme's agricultural data infrastructure development. Rwanda, as examined in the case studies section, has pursued digital agricultural transformation with the most ambitious government-led approach in sub-Saharan Africa, driven by its National Agricultural Policy and Smart Agriculture Strategy that positions digital technology as a central mechanism for transforming the productivity and market integration of smallholder farming systems.

The policy framework challenge of smart agriculture in developing country contexts is primarily one of coherence and coordination: the multiple agencies, programmes and financial instruments nominally aimed at supporting digital agricultural transformation are often fragmented, poorly coordinated and insufficiently connected to the on-the-ground realities of the farming communities they are designed to serve. Mudzielwana (2025), examining climate-smart food systems in South Africa, found that institutional impediments characterised by fragmented support systems and inadequate inter-agency coordination further complicated climate-smart agriculture policy implementation across administrative scales and that addressing these complexities necessitated integrated and multidimensional policy frameworks that fostered institutional synergies and ensured coherence across policy domains.

Adoption Dynamics: Who Adopts Smart Agriculture and Why

Understanding the adoption dynamics of smart agricultural technologies, including who adopts them, who does not and what determines the difference, is essential for assessing whether smart agriculture delivers its potential contribution to sustainable food system transformation or whether its benefits accrue primarily to the farming actors who are already best placed to improve their own performance. The adoption literature on smart agriculture draws on established frameworks from innovation diffusion theory, behavioural economics and agricultural development economics to explain the patterns of uptake and non-uptake observed in empirical studies.

Agyekum *et al.* (2024), in their systematic review of benefits and barriers to climate-smart agriculture adoption in West Africa, found that adoption was systematically shaped by a set of factors that collectively advantaged farmers who were already relatively well-resourced, educated and institutionally connected. Education level, farm size, access to extension services, access to credit, land tenure security and proximity to markets all positively predicted adoption,

while poverty, remoteness, limited formal education and insecure land tenure all negatively predicted it. This pattern of differential adoption, in which the farmers with the greatest absolute need for the productivity and resilience improvements that smart technologies provide are also those facing the greatest barriers to adopting them, is one of the most consequential findings in the smart agriculture adoption literature.

The gender dimension of smart agriculture adoption mirrors and often amplifies the broader pattern of differential adoption by socioeconomic advantage. Women farmers in sub-Saharan Africa face specific and compounding barriers to smart technology adoption that include lower mobile phone ownership rates, less access to formal credit and land title, greater time poverty from domestic responsibilities and less participation in the extension systems and farmer organisations through which technology information and training typically flow. Finizola e Silva *et al.* (2024) identified gender-responsive interventions as a priority for climate-smart agriculture policy, confirming that generic adoption support programmes that did not specifically address women farmers' distinctive constraints consistently underperformed in reaching and benefiting the female agricultural workforce.

Social learning and peer networks play a critical role in smart agriculture adoption dynamics that the individual-focused adoption literature sometimes underestimates. Farmers who observe trusted peers using smart technologies effectively are substantially more likely to adopt than those who encounter the same technologies through formal extension channels without the social proof of successful peer deployment. This social learning dynamic has important implications for the design of smart agriculture diffusion strategies: programmes that identify and support digitally capable farmers as community technology champions, enabling peer demonstration and peer-to-peer knowledge transfer, are likely to achieve broader and more sustained adoption than those that rely exclusively on formal extension channels.

Data Governance and Ethical Dimensions of Smart Agriculture

The data-intensive character of smart agriculture creates governance challenges that are distinct from those of earlier agricultural technology adoptions, because the data generated by smart agricultural systems, including detailed records of farm operations, soil conditions, crop performance, livestock health and farmer decision-making, is commercially valuable in ways that create potential conflicts of interest between the farmers who generate it and the technology providers and agribusiness firms who have access to it. Data governance in smart agriculture encompasses the legal frameworks, contractual arrangements, technical standards and institutional mechanisms through which questions of data ownership, access, use and commercialisation are determined.

Lai *et al.* (2025) found that different governance structures significantly influenced the design and effectiveness of digital traceability systems, with governance models that distributed control

over data across multiple supply chain actors producing more equitable outcomes than those that concentrated data access in the hands of dominant platform operators. The governance dimension of blockchain in agriculture was particularly instructive: blockchain's architectural promise of distributed, permissionless data access was frequently undermined in practice by the concentration of system design and maintenance in the hands of technology providers whose interests were not necessarily aligned with those of the smallholder farmers nominally served by the system.

The ethical dimensions of smart agriculture data collection and use extend beyond data governance to encompass the broader social implications of deploying surveillance and optimisation systems in farming communities whose members may not fully understand what data is being collected about them, how it is being used and who benefits from its commercial exploitation. The risk that smart agriculture technologies primarily serve to extract value from farming communities rather than to create value for them is a genuine concern that ethical frameworks for agricultural technology development need to address explicitly, alongside the more commonly discussed challenges of technical performance and economic return.

Theoretical Framework

This chapter's analysis of smart agriculture as a sociotechnical phenomenon is grounded in sustainability transitions theory and the multi-level perspective, which provide an analytical vocabulary for understanding how radical technological innovations emerge, encounter resistance and progressively reshape the sociotechnical systems they challenge. The multi-level perspective, developed by Frank Geels and subsequently applied extensively in the transitions literature, conceptualises technological change as occurring across three analytical levels: the niche, where radical innovations develop in protected spaces away from mainstream selection pressures; the regime, where incumbent technologies, institutions and practices are stabilised through mutual reinforcement; and the landscape, where broad social, economic and environmental trends create pressures on existing regimes.

Smart agriculture technologies are most productively understood as niche innovations that are progressively challenging the incumbent agricultural regime characterised by input-intensive conventional farming practices, commodity market structures and the institutional infrastructure of public extension services, agricultural research systems and rural credit markets that were designed for that regime. The multi-level perspective predicts that the diffusion of niche innovations into mainstream regime practice is shaped by the interaction between the technical performance of niche innovations, the landscape-level pressures, including climate change, food security concerns and sustainability imperatives, that create demand for regime transformation and the regime-level barriers, including institutional inertia, incumbent interest group resistance and the sunk costs of existing infrastructure, that constrain the pace and direction of transition.

This theoretical framework directs analytical attention to the structural conditions that determine whether smart agriculture technologies succeed in transforming agricultural regimes or remain confined to the advantaged niches in which they initially develop. It explains why countries with supportive governance environments, adequate infrastructure and coherent institutional frameworks are further advanced in smart agriculture adoption than those where these enabling conditions are absent, not primarily because the technologies perform differently in different contexts, but because the sociotechnical systems within which the technologies must operate are differently structured in ways that either facilitate or obstruct the transition dynamics that diffusion requires.

The political economy dimension of sustainability transitions is particularly important for understanding smart agriculture's uneven global diffusion. Transitions are not politically neutral processes; they create winners and losers and the actors who stand to lose from technological transformation often have both the motivation and the institutional capacity to obstruct it. In smart agriculture, the incumbent interests include conventional agricultural input suppliers, commodity traders and financial intermediaries whose business models depend on the information asymmetries and transaction cost structures that smart technologies threaten to disrupt. Understanding the politics of smart agriculture transitions, including who resists transformation and through what mechanisms, is as important for practical policy design as understanding the technical performance of the technologies themselves.

Case Studies

Case Study 1: Precision Agriculture Adoption in South Africa

South Africa provides one of the most instructive cases of smart agriculture adoption in the developing world because it combines relatively advanced agricultural technology infrastructure in its commercial farming sector with the substantial smallholder farming context, characterised by limited resources, insecure land tenure and inadequate institutional support, that characterises most of sub-Saharan Africa. The coexistence of these two farming sectors within a single national agricultural system creates a natural comparison case that illuminates how the same policy environment and technological landscape produce radically different adoption outcomes depending on the socioeconomic and institutional conditions of the adopting population.

Dyanty *et al.* (2025) examined the adoption and scaling of climate-smart agriculture innovations among smallholder farmers in South Africa, finding that while CSA interventions including conservation agriculture, drought-tolerant crop varieties and precision irrigation had demonstrated positive outcomes in productivity, food security and climate resilience, adoption remained uneven and limited among smallholder farmers. Key barriers included insecure land tenure that reduced farmers' willingness to invest in technologies whose returns required multi-year payback periods, insufficient extension and climate information services to support adoption

decisions, limited access to credit and inputs and fragmented institutional support from multiple government agencies whose programmes were insufficiently coordinated to provide comprehensive adoption support.

The South African case also illustrates the governance challenges of smart agriculture data systems in contexts characterised by significant power asymmetries between large agribusiness actors and smallholder farming communities. Commercial precision agriculture data platforms deployed in South Africa have predominantly served the commercial farming sector, where farm operators have the financial resources, technical literacy and institutional connections needed to engage with data-intensive management systems. The extension of these platforms to smallholder contexts has been limited by the same barriers that constrain technology adoption more broadly and by the additional challenge that commercial data platforms designed for commercial farming contexts do not automatically meet the specific needs of smallholder farming systems characterised by smaller plot sizes, less capital-intensive production methods and different information requirements.

The policy response to this adoption challenge in South Africa has included the development of the Electronic Agricultural Land Information System, investments in the Agricultural Research Council's digital agricultural research capacity and the integration of smart agriculture objectives into the Department of Agriculture, Land Reform and Rural Development's strategic plans. However, these policy initiatives have not yet produced the systematic transformation of smallholder agricultural practice that their stated objectives imply, confirming the finding from the broader adoption literature that policy intention without adequate implementation infrastructure, including extension capacity, financial instruments and institutional coordination, produces limited outcomes.

Case Study 2: Climate-Smart Agriculture Policy in West Africa

West Africa presents a case study in the political economy of smart agriculture policy adoption that illustrates both the earnestness of international and national commitment to climate-smart agricultural transformation and the structural difficulties of translating that commitment into farm-level practice change at the scale needed to address the region's food security and climate vulnerability challenges. The World Bank's financing of US$3.8 billion in climate-smart agriculture projects across 30 African countries between 2016 and 2018, alongside the African Union Development Agency's vision of 25 million farming families adopting climate-smart agriculture by 2025, established ambitious policy targets whose achievement has been significantly constrained by the structural conditions of smallholder farming across the region.

Agyekum *et al.* (2024), in their systematic review of benefits and barriers to climate-smart agriculture adoption in West Africa, found that the evidence base on adoption was predominantly positive in demonstrating that climate-smart practices enhanced food security and incomes where

adoption occurred, while simultaneously documenting that the barriers to adoption were substantial and persistent. The primary barriers identified across the reviewed studies included lack of knowledge about available technologies and practices, insufficient financial resources to invest in technology adoption, inadequate access to inputs and markets, insufficient extension service coverage and the pervasive risk aversion that characterised farming households whose survival depended on not losing their existing meagre harvests to unproven new approaches.

The Senegalese case examined by Diop *et al.* (2025), studying factors driving climate-smart agriculture adoption among smallholder farmers in Koumpentum, provided granular insight into how these barriers operated at the farm level. Smallholder farmers identified lack of knowledge, lack of resources and insufficient financial resources as the primary obstacles to adoption, with these barriers operating in combination in ways that made addressing any single barrier in isolation insufficient. Farmers who received extension information about improved varieties could not adopt them without credit to purchase seeds; farmers who had credit access could not adopt water-efficient irrigation without the infrastructure investments that credit alone could not fund; and farmers who had both information and resources faced the additional challenge of uncertain and volatile output markets that reduced the economic returns to improved production that made technology adoption financially rational.

The policy lesson of the West Africa case is not that climate-smart agriculture programmes are ineffective but that their effectiveness depends on the comprehensiveness of the enabling environment they create. Programmes that address only one or two of the multiple interconnected barriers to adoption consistently underperform relative to those that provide integrated support spanning information, finance, inputs, infrastructure and market access simultaneously. This integrated approach is more expensive and institutionally demanding than single-component programmes, but the evidence consistently confirms that it is more effective at producing the sustained adoption that transforms agricultural practice rather than generating temporary uptake that collapses when programme support ends.

Case Study 3: Blockchain and Digital Traceability in the European Agri-Food Supply Chain

The European agri-food sector provides the most advanced case study of blockchain-enabled smart agriculture in practice, reflecting the combination of robust digital infrastructure, strong regulatory frameworks for food safety and sustainability, high consumer demand for food transparency and significant private sector investment in supply chain technology that makes Europe the leading region for agricultural blockchain implementation. The European Union's regulatory environment, including the Farm to Fork Strategy's food system transformation objectives and the forthcoming Digital Product Passport requirements that will mandate

blockchain-verified lifecycle data for agricultural imports by 2027, is creating both the incentive and the regulatory obligation for blockchain adoption across the food supply chain.

Lai *et al.* (2025) found that digital traceability systems in the European agri-food sector were enhancing transparency, compliance and quality control by enabling real-time monitoring of products through the supply chain, with different governance structures significantly influencing their design and effectiveness. Their governance framework analysis found that traceability systems designed around distributed governance, in which multiple supply chain actors shared control over data systems and decision-making authority, produced more equitable outcomes and more robust supply chain transparency than those concentrated in the hands of dominant platform operators. This governance finding is directly relevant to the deployment of blockchain in contexts where power asymmetries between small agricultural producers and large agribusiness firms risk reproducing the same value extraction dynamics that technological traceability systems are nominally designed to disrupt.

The Walmart and IBM Food Trust blockchain case, which reduced the time to identify the origin of food products from six days to 2.2 seconds, became one of the most widely cited demonstrations of blockchain's practical value for food supply chain management. The system's capacity to enable rapid traceability in the event of food safety incidents, reducing both the scope of recall operations and the duration of consumer exposure to contaminated products, provided a compelling commercial case for blockchain adoption that has driven substantial industry investment in the years since. However, the governance structure of the Walmart-IBM model, in which the technology infrastructure was controlled by a dominant retailer and its technology partner, illustrates the concentration-of-power risks that distributed ledger technology's architectural promises do not automatically resolve in practice.

The European case also illustrates the challenge of ensuring that the benefits of blockchain-enabled supply chain transparency reach the smallest and most vulnerable actors in agricultural supply chains. Consumer premiums for blockchain-certified produce of 23 to 41 %, represents genuine market value that could potentially be captured by producing farmers if governance structures allowed them to participate in and benefit from certification systems. In practice, the high technical complexity and implementation costs of blockchain systems, alongside the power asymmetries that characterise most agricultural value chains, mean that the economic benefits of transparency certification frequently accrue primarily to processors, retailers and technology vendors rather than to the farming households at the bottom of the supply chain.

Implications

The analysis of smart agriculture across its technological, policy and practice dimensions generate a set of implications for policymakers, practitioners, researchers and technology

developers that collectively point toward the conditions under which smart agriculture can deliver on its potential for sustainable and equitable food system transformation.

For policymakers, the most important implication is that smart agriculture policy must be comprehensive and integrated rather than technology-focused and siloed. The evidence consistently confirms that smart agricultural technologies deliver their greatest benefits when they are deployed within enabling environments that simultaneously address infrastructure, finance, human capacity and institutional coordination. Single-technology programmes and single-barrier interventions consistently underperform relative to integrated approaches, because the barriers to adoption are multiple, interconnected and mutually reinforcing in ways that addressing any one in isolation leaves the others intact. Effective smart agriculture policy requires the kind of cross-departmental coordination, long-term investment horizon and commitment to monitoring and adaptive management that is institutionally demanding but empirically necessary.

For agricultural development practitioners and international organisations, the implication is that the equity dimension of smart agriculture adoption requires explicit, targeted attention rather than the assumption that broad programmes will automatically reach the most vulnerable farming populations. Women farmers, smallholder farmers in remote areas, farmers in fragile political and institutional contexts and farmers without formal land tenure all face distinctive combinations of barriers that require specifically designed responses rather than adaptations of programmes designed primarily for better-resourced farming contexts. Building genuine understanding of the specific conditions of marginalised farming populations into the design of smart agriculture programmes from the outset, rather than retrofitting equity considerations after the fact, is the approach most likely to produce equitable outcomes.

For technology developers and agribusiness firms investing in agricultural digitalisation, the governance implications of smart agriculture data systems deserve priority attention alongside technical performance considerations. Technologies that concentrate data control in the hands of platform operators or dominant supply chain actors, even when they deliver genuine technical benefits, risk reproducing and amplifying the power asymmetries that characterise the food systems they are entering. Governance architectures that distribute control over agricultural data systems across multiple stakeholders, including farming communities, are more equitable and ultimately more sustainable than those that create new forms of technological dependency without creating new forms of farmer empowerment.

For researchers, the comparative analysis in this chapter identifies several significant gaps in the smart agriculture evidence base. Longitudinal studies tracking the sustained impacts of smart agriculture technology adoption over multiple agricultural seasons, beyond the single-season impact studies that dominate the literature, would provide more reliable evidence about whether

adoption delivers durable productivity and income improvements or produces temporary gains that dissipate as programme support ends. Research that examines the distributional impacts of smart agriculture adoption across different farmer types within the same policy and technology context would provide the equity-focused evidence that policy design currently lacks. And systematic research on the governance dimensions of agricultural data systems, including how different data governance models affect the distribution of benefits across supply chain actors, would address one of the most practically consequential but least empirically grounded questions in the field.

Conclusion

Smart agriculture is neither the silver bullet that its most enthusiastic advocates claim nor the false promise that its most sceptical critics assert. It is a genuinely transformative set of technologies whose capacity to improve agricultural productivity, resource use efficiency and climate resilience is well-documented and substantial. It is also a set of technologies whose distribution of benefits, across farm sizes, farming systems, geographies and socioeconomic groups, is profoundly shaped by the policy environments, power relations and institutional arrangements within which it is deployed. Getting those arrangements right is the decisive challenge of smart agriculture in the current decade.

The three case studies examined in this chapter, precision agriculture adoption in South Africa, climate-smart agriculture policy in West Africa and blockchain-enabled traceability in European agri-food supply chains, together confirm that smart agriculture's potential is most fully realised in contexts where enabling policy frameworks provide comprehensive support, where institutional arrangements distribute technology benefits equitably across supply chain actors and where governance structures empower farming communities rather than merely extracting value from them. Where these conditions are absent, smart agriculture risks delivering its greatest benefits to the farming actors who are already best placed to improve their own performance, while leaving the smallholder farmers who most need productivity and resilience improvements further behind.

Realising the transformative potential of smart agriculture for sustainable food system development requires treating it as a political and institutional challenge at least as much as a technological one. The question is not primarily whether the technologies work, the evidence confirms that they do, but whether the policy frameworks, institutional arrangements and governance structures surrounding their deployment create conditions for inclusive transformation or reproduce the inequalities that have characterised agricultural development for generations. Answering that question well is the most important task facing smart agriculture researchers, policymakers and practitioners in the years ahead.

References

1. Agyekum, T. P., Antwi-Agyei, P., Dougill, A. J., & Stringer, L. C. (2024). Benefits and barriers to the adoption of climate-smart agriculture practices in West Africa: A systematic review. *Climate Resilience and Sustainability*, *3*(3), e279.
2. Miller, T., Mikiciuk, G., Durlik, I., Mikiciuk, M., Łobodzińska, A., & Śnieg, M. (2025). The IoT and AI in agriculture: The time is now: A systematic review of smart sensing technologies. *Sensors*, *25*(12), 3583.
3. Duguma, A. L., & Bai, X. (2024). How the internet of things technology improves agricultural efficiency. *Artificial Intelligence Review*, *58*(2), 63.
4. Diop, A., Cisse, M., & Ndiaye, M. (2025). Factors driving climate-smart agriculture adoption: A study of smallholder farmers in Koumpentum, Senegal. Frontiers in Agronomy, 7, Article 1552720. https://doi.org/10.3389/fagro.2025.1552720
5. Finizola e Silva, M., Van Schoubroeck, S., Cools, J., & Van Passel, S. (2024). A systematic review identifying the drivers and barriers to the adoption of climate-smart agriculture by smallholder farmers in Africa. *Frontiers in Environmental Economics*, *3*, 1356335.
6. Lai, M. B., Vergamini, D., & Brunori, G. (2025). Food supply chain: a framework for the governance of digital traceability. *Foods*, *14*(12), 2032.
7. Mansoor, S., Iqbal, S., Popescu, S. M., Kim, S. L., Chung, Y. S., & Baek, J. H. (2025). Integration of smart sensors and IOT in precision agriculture: trends, challenges and future prospectives. *Frontiers in Plant Science*, *16*, 1587869.
8. Dyanty, T., Agholor, I. A., Nkambule, T. B., Nkuna, A. A., Nkosi, M., Ndlovu, S. M., ... & Makhubu, T. H. (2025). Socio-economic determinants of climate change adaptation strategies among smallholder farmers in Mbombela: a binary logistic regression analysis. *Climate*, *13*(5), 90.
9. Mudzielwana, R. V. (2025). Climate-smart food systems: integrating adaptation and mitigation strategies for sustainable agriculture in South Africa. *Frontiers in Sustainable Food Systems*, *9*, 1580516.
10. Xu, J., Cui, Y., Zhang, S., & Zhang, M. (2024). The evolution of precision agriculture and food safety: a bibliometric study. *Frontiers in Sustainable Food Systems*, *8*, 1475602.

SILENT WINGS OF THE NIGHT: MOTHS AS HIDDEN POLLINATORS

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Abstract

Pollination is a vital ecological process that ensures plant reproduction, biodiversity conservation, and agricultural productivity. While bees are widely recognized as major pollinators, the contribution of moths has remained comparatively overlooked. Moths, representing nearly 90% of Lepidoptera diversity, function as efficient nocturnal and crepuscular pollinators across natural and agro-ecosystems. Their long proboscis, hairy body surfaces, enhanced night vision, and highly sensitive olfactory antennae enable them to locate flowers, access concealed nectar, and transfer pollen effectively over long distances. Flowers pollinated by moths are typically pale-coloured, tubular, nectar-rich, and release strong fragrance during the night, reflecting specialized adaptations known as sphingophily and phalaenophily. Recent studies demonstrate that moths significantly contribute to pollination of crops such as gourds, strawberry, apple, and avocado, while also supporting wild flora in field margins, hedgerows, and semi-natural habitats. In several plant species, nocturnal moth pollination has been shown to equal or exceed diurnal pollination in seed set, fruit quality, and pollen dispersal efficiency. Moths also promote gene flow between distant plant populations, thereby reducing inbreeding depression and enhancing ecosystem resilience. Case studies from India, Europe, the Himalayas, and South America further highlight the diversity and ecological significance of moth-mediated pollination networks. Despite their importance, moth pollination systems remain understudied and vulnerable to habitat loss, pesticide exposure, and artificial light pollution. Conservation of moth populations and their habitats is therefore essential for sustaining ecosystem services and ensuring pollination security. Recognizing moths as "silent wings of the night" broadens our understanding of pollinator diversity and emphasizes the need for integrated conservation strategies that include both diurnal and nocturnal pollinators.

Keywords: Moths, Nocturnal pollination, Lepidoptera, Pollinator diversity, Ecosystem services, Sphingophily, Phalaenophily, Crop pollination.

1. Introduction

Pollination is the transfer of pollen to the stigma of a conspecific flower, while pollination ecology examines the mutual relationships among flowers, pollinators, and environmental factors. It is a long-term co-evolutionary process between flowering plants and pollinators that has developed over millions of years. Insects are considered the most effective pollinators and play a major role in maintaining biodiversity. Besides insects, wind, birds, and bats also act as pollination agents and help disperse pollen, spores, and seeds. Pollinator attraction and efficiency are influenced by floral traits such as shape, size, colour, odour, nectar, and pollen rewards, while pollinator effectiveness depends on vision, olfaction, taste, anatomy, feeding preference, behaviour, and learning ability. Environmental factors such as altitude, temperature, light, wind, and rainfall also affect flower visitation, foraging behaviour, and pollination success (Faheem *et al.,* 2004).

Most flowering plants are pollinated by animals, whereas only a smaller proportion depend on abiotic agents such as wind. Out of an estimated 352,000 angiosperm species, about 308,006 species (87.5%) are animal-pollinated. These plant–pollinator interactions are essential for ecosystem stability and agricultural productivity, making pollinator decline a major concern for both ecologists and policy makers (Ollerton *et al.,* 2011).

Lepidoptera are important flower visitors, mainly feeding on nectar. This order contains around 165,000 species, representing nearly 10% of global insect diversity. However, most research has focused on butterflies, while moths account for nearly 90% of Lepidoptera species. As a result, nocturnal pollination systems have received comparatively less attention, though moths and bats are known to play significant pollination roles (Ribas Marques *et al.,* 2020).

Moths are important pollinators in many ecosystems worldwide and can transport pollen over longer distances than many other insects, promoting gene flow among plant populations. Among them, Noctuidae and Sphingidae are common nocturnal flower visitors (Ribas Marques *et al.,* 2020). Traditionally, moth pollination is classified into two syndromes: Sphingophily (hovering sphingid moths) and Phalaenophily (settling moths other than sphingids), with sphingophilous plants being the most well-known examples (Macgregor *et al.,* 2015).

Comparison Between Sphingophilous and Phalaenophilous Flower Morphology

Sphingophily and phalaenophily are two pollination syndromes involving moths. Sphingophily refers to pollination by sphinx or hawkmoths, while phalaenophily refers to pollination by other nocturnal moths. Flowers adapted to both syndromes are typically pale or white, tubular in shape, and release a strong sweet fragrance at night, which helps attract their nocturnal pollinators (Macgregor *et al.,* 2015).

2. Comparison Between Bee Flowers and Moth Flowers

Bee flowers and moth flowers show distinct adaptations to their pollinators. Bee flowers are usually brightly coloured, fragrant during the day, and often provide a landing platform suited to bee behaviour. In contrast, moth flowers are commonly white or pale for better visibility at night, release fragrance during nighttime, and often have tubular shapes that suit the long proboscis of moths (Ollerton *et al.,* 2011).

3. Salient Features of Moth Adaptations

3.1 Moth Species Active Throughout the Day

Moths are important pollinators in many ecosystems because they exhibit diurnal, crepuscular, and nocturnal activity patterns. Several species visit flowers continuously throughout the day, thereby contributing to pollination over extended periods (Hahn and Bruhl, 2016).

3.2 Proboscis

Moths generally possess a long proboscis, which in some species may exceed their body length. This adaptation enables them to access nectar and pollen from a wide variety of flowers, including open flowers, long-tubed flowers, and flowers with deeply concealed nectar sources (Hahn and Bruhl, 2016).

3.3 Long-Distance Pollination

Moths have been observed to disperse pollen over longer distances compared to many diurnal pollinators in several plant species. This long-range pollen transfer can enhance gene flow and help maintain genetic diversity within and between plant populations (Hahn and Bruhl, 2016).

3.4 Pollen Transport

While feeding, moths typically rest on flowers, and their hairy bodies frequently come into contact with the reproductive structures of the flower. A large proportion of pollen is carried on the ventral thorax, commonly referred to as the insect's chest, from where it can be efficiently deposited during later flower visits. Certain plants may rely specifically on moths that transport pollen in this manner (Hahn and Bruhl, 2016).

3.5 Diverse Group of Potential Pollinators

Moths have been reported feeding on nectar from a broad range of plant families, including Adoxaceae, Apiaceae, Asteraceae, Boraginaceae, Ericaceae, Fabaceae, Lamiaceae, Malvaceae, Primulaceae, Rosaceae, and Scrophulariaceae, among others, demonstrating their value as a diverse group of potential pollinators (Hahn and Bruhl, 2016).

4. Mechanisms for Night Time Pollination Interactions

4.1 Moths use their enhanced night vision to navigate and find flowers in the dark

In superposition eyes, many facets are involved a single rhabdom instead receives light rays that enter a large number of corneal lenses (usually several hundred that form a wide pupil like 'superposition aperture'. And here in lies the optical advantage of superposition eyes for vision

in dim light—the light signal on each rhabdom is boosted several hundred times. Not surprisingly, nocturnal insects very typically have this type of compound eye, including many beetles and most moths, such as our three colour-seeing hawkmoths. As part of their response to a life at night, the eyes of these insects have evolved much larger facets and significantly wider rhabdoms than found in their similarly sized day-active relatives, boosting their photon catch by about 30 times. Obviously, a boost by 30 times, or even hundreds of times (as with superposition optics), does provide a great improvement in visual SNR (Warrant and Somanathan, 2022).

4.2 Moths antennae are equipped with olfactory neurons that detect floral scents from great distances

Generally, antennae are called as lepidopteran nose due to the accommodation of large number of olfactory neurons, up to 100000 sensilla, each containing a number of sensory cells, functioning as odour detectors and molecular sieve. The antenna displays different outer morphology in the different types of Lepidoptera. Olfactory receptors are also present on the adult moths on the palp region and referred as, labial palp pit (Hansson, 1995).

4.3 Flowers release specific scents at night to attract moths for pollination

Floral scent plays an important role in many nocturnal plant–pollinator mutualisms. The volatile chemistry of moth-pollinated flowers has been studied in several taxa. These flowers commonly release blends of acyclic terpene alcohols such as linalool, aromatic alcohols including benzenoids, derived esters, and small amounts of nitrogen-containing compounds. Some volatiles, especially linalool, can attract multiple nocturnal and diurnal visitors such as moths, bees, mosquitoes, and thrips.

The ecological significance of these compounds becomes clearer when the timing of scent release is considered, as floral emissions are often rhythmic. For example, in *Petunia* spp. (Solanaceae), which are pollinated by hawk-moths (Sphingidae), daytime scent emissions are much less attractive than nighttime emissions. These rhythmic patterns are controlled by an internal gene-regulated circadian clock and are particularly common in long-lived flowers associated with nocturnal pollinators.

Circadian emission of floral volatiles is considered an adaptation to match nocturnal pollinator activity, though it may also help reduce attraction of, or repel, diurnal herbivorous insects in some species (Macgregor and Scott-Brown, 2020).

Case study I: Flower scent composition in night-flowering Silene species (Caryophyllaceae)

Jürgens *et al.* (2002) studied floral scent composition in 13 night-flowering species of *Silene* (Caryophyllaceae), a large genus of about 700 species pollinated by bees, flies, moths, hawkmoths, mosquitoes and birds, with moths being the dominant visitors. The objective was to relate floral scent chemistry with pollination biology and phylogeny. Night-flowering species were selected based on nocturnal flower opening, pale corolla colour, increased evening scent

emission and observation of night visitors. Floral volatiles were collected between 21:00 and 01:00 h using air pumps and adsorbent cartridges, then analysed by gas chromatography–mass spectrometry. A total of 69 compounds were detected, of which 52 were identified. Floral scents varied qualitatively and quantitatively among species, but benzenoids and isoprenoids dominated most taxa. Major compounds included benzaldehyde in *S. subconica*, *S. succulenta*, *S. sericea*, *S. vulgaris* and *S. nutans*; methyl benzoate dominant in *S. saxifraga* and abundant in *S. succulenta*; benzyl acetate in *S. dichotoma*, *S. nutans*, *S. italica* and *S. latifolia*; benzyl alcohol in *S. viscosa*; and p-cresol only in *S. dichotoma*. Most identified compounds are common floral volatiles associated with moth pollination, such as linalool, benzyl alcohol, 2-phenylethanol and related esters. Since all species had calyx lengths below 2.5 cm, they were not highly specialized for sphingids and likely attracted multiple pollinators. Species visited by Noctuidae and Sphingidae showed no clear scent differences. The study concluded that neither pollination biology nor phylogeny alone determined floral scent patterns, and these *Silene* species represent generalist moth-pollinated flowers without major scent differences between long- and short-tubed forms (Jürgens *et al.,* 2002).

4.4 Moths can detect the warmth of flowers, guiding them to nectar sources

Nocturnal pollination occurs under conditions of reduced light and cooler ambient temperatures. Since most pollinating insects are ectothermic, the ability to detect flowers that provide floral warmth can offer a foraging advantage. Some flowers retain environmental heat or generate it through thermogenesis, and such heat-producing species—particularly those in cooler habitats—may be preferentially visited by ectothermic pollinators. Besides acting as a thermal reward and providing shelter, thermogenesis also enhances the release of floral scent volatiles, potentially improving pollinator attraction. Thermogenesis is found in both gymnosperms and angiosperms, including cycads such as members of Zamiaceae. Although separating the specific role of heat from other floral cues is challenging, it has been suggested that nectar-feeding insects capable of detecting infrared (IR) radiation (e.g., mosquitoes and other blood-feeding taxa) may use thermal signals to locate and track nectaries of thermogenic flowers at night. Plants may thus exploit pre-existing sensory modalities to enhance pollinator attraction (Macgregor and Scott-Brown, 2020).

4.5 Nectar-rich flowers provide energy for moths while ensuring pollination

Night flowering species had the greatest nectar sugar concentration in the middle of the night and suggested that sucrose- rich nectar in tubular flowers may be an adaption to pollination by long-tongued pollinators such as moths (Buxton *et al.,* 2022).

5. Significance of Moth Pollination

5.1 Ecological Armageddon

Diurnal pollination services are likely to be critically affected by declines in insect distribution and abundance. Global insect decline has been labelled ‘Ecological Armageddon’, however the

rate and generality of decline and the driving forces implicated are still poorly understood. The accuracy surrounding the narrative of the 'Ecological Armageddon' has since come under scrutiny (Buxton *et al.,* 2022).

5.2 Metabolic Restrictions in Bees

Bees are active potential pollinators and also pollen is actively collected by them to feed their larvae and therefore they might have more metabolic restriction than moths when choosing the pollen sources (Ribas-Marques *et al.,* 2020).

5.3 To Mitigate Inbreeding Depression in Populations

Inbreeding depression is the reduction in the biological fitness of the individuals. Continuous selfing will results in inbreeding depression that in turn will reduce the biological fitness of the individual (Macgregor *et al.,* 2015).

5.4 Enhancing Pollination Efficiency

Moths will take very less pollen grains and and they deposit more pollen grains without compromising in reproductive success and ensures the greater seed set in moth pollinated flowers (Macgregor *et al.,* 2015).

5.5 optimizing pollination quality

Moths have very less pollen ovule ratio and maximum of 600:1 whereas, bees have more pollen ovule ratio and they waste majority of pollen grains in corbiculae and they are termed as ugly pollinators (Macgregor *et al.,* 2015).

5.6 Bimodal or mixed pollination system

Some of the flower morphology has been adopted to they need two functional pollinator groups to complete pollination process. In such cases moths act as one of the functional pollinator groups, where moths and bats are the prominent functional pollinator groups that are present in ecosysytem (Macgregor *et al.,* 2015).

Case study II: Nocturnal insect pollinator diversity in bottle gourd and ridge gourd in southern Andhra Pradesh (Subhakar and Sreedevi, 2015).

Studies were conducted to assess insect pollinator diversity in ridge gourd and bottle gourd at the Insectary, Department of Entomology, S. V. Agricultural College, ANGRAU, Tirupati, during 2010–11. Both crops were grown under field conditions in divided plots with recommended agronomic practices, including vermicompost and NPK application, and seed treatment with Captan. Ridge gourd was planted in pits with 2 m spacing.

Results showed that Lepidoptera dominated the pollinator community (70.07% in bottle gourd and 76.68% in ridge gourd), mainly comprising pyralid, crambid, sphingid, noctuid, and pierid species. Other important groups included Hymenoptera (Oecophylla smaragdina), Coleoptera (Aulacophora foveicollis), Dictyoptera (Mantis religiosa), and Orthoptera species. Hippotion celerio and Diaphania indica were identified as generalist pollinators, while Arthoscista hilarialis

and Glyphodes bivitralis acted as specialist pollinators. Efficient pollination activity of sphingids, pyralids, and noctuids was synchronized with floral anthesis in both crops during evening hours (1700–1800 h), supported by strong floral scent and nectar rewards.

A comparative study on strawberry (Fijen *et al.,* 2023) highlighted the importance of nocturnal pollination. Plants were grown in a randomized block design with four treatments: no pollination, night pollination, day pollination, and open pollination, using insect-proof cages. A total of 626 fruits were harvested. While total yield did not differ significantly among treatments, individual fruit weight and size were lowest in non-pollinated plants and highest under open and night pollination. Nocturnal and diurnal pollinators contributed equally to fruit quality, particularly under high fruit load conditions, indicating complementary roles in enhancing strawberry productivity.

Case study IV: Diurnal and nocturnal pollination of *Silene alba* (Caryophyllaceae) (Young, 2002).

A study was conducted to evaluate the relative effectiveness of diurnal and nocturnal pollinators on reproductive success in *Silene alba*. Female plant branches were enclosed with bridal veil nets in July 1994 and subjected to four treatments: (T1) nocturnal pollination allowed by bagging during daytime only, (T2) diurnal pollination allowed by bagging at night only, (T3) open pollination without bagging, and (T4) complete exclusion of pollinators (bagged day and night). Fruits were collected 30 days after pollination, and seed number and seed weight were recorded. Floral traits such as corolla width were also measured to assess pollinator preference.

Results showed that all flowers produced fruits, but seed set varied significantly with pollinator type. Moth-visited flowers produced more than twice the seed set compared to bee-visited flowers. Flowers exposed to both diurnal and nocturnal visitors showed seed production similar to those visited only by moths, indicating that nocturnal moths are the primary and more effective pollinators. Interestingly, even flowers excluded from major pollinators produced some seeds, likely due to small insects such as thrips entering the mesh.

No significant difference was observed between continuously bagged flowers and those exposed only to nocturnal pollination, suggesting limited contribution of diurnal insects (bees, wasps, and flies) to seed production. Moths were also more efficient in pollen transfer and movement between flowers compared to diurnal insects, which often showed less effective foraging patterns.

Major nocturnal pollinators included *Hyles gallii*, *Autographa californica*, *Leucania multilinea*, and *Hadena variolata*, active mainly around 9:20 PM. Diurnal visitors such as *Apis mellifera*, *Bombus* spp., syrphid flies, and wasps were active from early morning (7:00 AM) to late afternoon (5:00 PM).

Overall, the study demonstrated that nocturnal moths are more effective pollinators than diurnal insects in *Silene alba*, influencing higher seed production and more efficient pollen dispersal, highlighting strong selection for pollination syndromes favoring moth visitation.

Case Study V: Settling moths are the vital component of pollination in Himalayan ecosystem of North-East India, pollen transfer network approach revealed (Singh *et al.,* 2022).

The role of Indian moths in pollination is still poorly understood. This study investigated the contribution of settling moths to pollination networks in the Himalayan ecosystems of North-East India, focusing on angiosperm families, seasonal variation, and altitudinal gradients in pollen-carrying capacity. Data were collected from 24 sites across Arunachal Pradesh, North Bengal, and Sikkim over 13 months (September 2018–October 2019) using vertical sheet light traps with 160-W mercury vapour lamps. Sampling covered three seasons: pre-monsoon, monsoon, and post-monsoon, across a wide altitude range (0–3000 m).

Moths were collected from 6 PM to 6 AM, processed, and their proboscis was isolated for pollen analysis using basic fuchsin staining and light microscopy. This method minimized contamination and enabled accurate identification of pollen grains retained within the proboscis. A total of 140 moth species belonging to 18 subfamilies and 6 families were identified as pollen carriers (termed pollen transporter moth species, PTMS). Among them, 91 species were classified as potential pollinator moth species (PPMS), each carrying five or more pollen grains. These moths carried pollen from 21 plant families, with Betulaceae (39.89%) being the most dominant, followed by Fabaceae (26.62%), Rosaceae (15.44%), and Ericaceae (7.66%). Family-wise, PPMS representation was highest in Geometridae (67.92%), followed by Noctuidae (62%), Erebidae (62%), Crambidae (57.14%), Drepanidae (42.85%), and Nolidae (100%). Most moths carried pollen from one or two plant families, while a few species carried up to five. Notably, *Teliphasa* sp. and *Cuculia* sp. carried the highest pollen loads (>1000 grains).

Overall, moths accounted for about 65% of effective pollen transporters, highlighting their significant role in Himalayan pollination networks. Geometridae and Erebidae were identified as key pollinator groups, with frequent transport of even wind-pollinated Betulaceae pollen. The study indicates strong moth–plant interdependence, suggesting that decline in moth diversity could negatively impact plant reproductive success and ecosystem stability.

Case Study VI: The secret pollinators: an overview of moth pollination with a focus on Europe and North America (Hahn and Bruhl, 2016).

Moths are recognized as important but understudied pollinators in many ecosystems. This study reviewed plant–moth pollination interactions in Europe and North America to understand their ecological role, with a focus on both settling moths and hawkmoths. A literature survey was conducted using Web of Knowledge along with related search terms such as “moth pollination

agriculture" and "moth pollination Europe." More than 300 publications and books were screened to compile documented plant–moth interactions. The review identified 227 pollination interactions involving 129 moth species across seven families. The majority of interactions were recorded in Noctuidae (56 species) and Sphingidae (32 species), while about 25% involved other families, including microlepidopterans. Although hawkmoths have been studied more extensively, settling moths represent a highly diverse and under-researched group of pollinators. In total, 61 plant species from 14 families were associated with moth pollination. The highest representation was found in Orchidaceae (22 species) and Caryophyllaceae (16 species), with orchids showing strong dependence on Lepidoptera, particularly in the subfamily Orchidoideae.

The findings highlight that moths are widespread flower visitors capable of contributing significantly to pollination services, including in specialized plant groups. However, their ecological role is likely underestimated due to limited research. The study suggests that future work should include both natural and agro-ecosystems, as moths may play an important role in maintaining biodiversity, even if they are not primary crop pollinators in Europe and North America.

Case Study VII: Crane flies and microlepidoptera also function as pollinators in *Epidendrum* (Orchidaceae: Laeliinae): the reproductive biology of *E. avicula* (Pansarin and Pansarin, 2017).

A study was conducted to examine the role of microlepidopterans in the pollination of the self-incompatible orchid *Epidendrum avicula*, which does not set fruit through self-pollination. The work was carried out in a disturbed gallery forest near Itirapina, Brazil, and under controlled conditions at the University of São Paulo Orchid House.

Four field-collected plants were observed during the 2012, 2014, and 2015 flowering seasons. Floral visitors were recorded and collected for identification, although exact visitation rates of microlepidoptera and flies could not be quantified due to identification constraints. A breeding system experiment (2013) included four treatments: untouched flowers, manual self-pollination, emasculation (apomixis test), and cross-pollination, with 100 flowers per treatment.

Results showed no fruit or seed set in the first three treatments, confirming complete self-incompatibility and absence of apomixis. Cross-pollination produced 56% fruit set and 59.1% viable seeds, indicating obligatory outcrossing for reproduction. The flowers were visited mainly by tipulid flies and nectar-feeding microlepidopterans. Both groups feed on nectar from a tubular floral structure and, after pollinarium removal, often become temporarily trapped by the proboscis, reducing immediate revisits and limiting geitonogamy. This behavior, along with floral mechanisms, promotes efficient pollen transfer while minimizing pollen loss.

Although visitors belong to different insect orders, they function similarly as pollinators and are considered a single functional group. Thus, *E. avicula* exhibits an apparently generalized

pollination system, but with functionally specialized interactions that influence floral evolution and reproductive success.

Case study VIII: Reproductive biology of *Echinopsis terscheckii* (Cactaceae): the role of nocturnal and diurnal pollinators (Ortega-Baes *et al.,* 2010).

This study investigated the reproductive biology and pollination system of *Echinopsis terscheckii*, a long-lived columnar cactus endemic to the semi-arid regions of northwest Argentina. The species bears nocturnal, funnel-shaped flowers and was hypothesized to have a generalized pollination system involving both nocturnal and diurnal visitors. The study assessed floral traits, breeding system, pollinator dependency, and the relative contribution of nocturnal and diurnal visitors to fruit and seed set. Field experiments were conducted in November 2000 using five treatments: natural pollination, nocturnal-only access, nocturnal hand cross-pollination, diurnal-only access, and diurnal hand cross-pollination, each with 10 bagged buds from five plants. Additional observations of floral visitors were made from 2000–2002.

Nocturnal moths were sampled using UV light traps, and pollen transfer was assessed through pollen grains on insect bodies and moth scales on stigmas. Diurnal visitors were recorded through direct observations and insect collections. Results showed significant variation in fruit and seed set among treatments. Nocturnal pollination consistently produced higher fruit set and seed output than diurnal pollination, while hand-pollination treatments showed no major differences between day and night. The species was confirmed as self-incompatible, relying entirely on pollinators for reproduction. Flower visitors included moths, bees, birds, and beetles. However, moths (mainly Noctuidae and Sphingidae) were the most effective pollinators, supported by higher reproductive success under nocturnal access and strong evidence of pollen transfer. Bees, particularly *Apis mellifera*, acted mainly as pollen thieves without effective pollination. Major nocturnal pollinators included species of Noctuidae, Sphingidae, Saturniidae, and Geometridae, while diurnal visitors were mainly bees such as *Apis mellifera*, *Xylocopa*, and *Bombus* species.

Overall, the study demonstrates that although *E. terscheckii* receives visits from both nocturnal and diurnal animals, moths are the primary and most effective pollinators, providing the first clear evidence of moth-dominated pollination in the genus *Echinopsis*.

Comparison Between Three Obligatory Mutualisms

The family Phyllanthaceae includes more than 518 species with nocturnal flowering, and pollination is carried out exclusively by moths of the genus *Epicephala* (Gracillariidae), which transport pollen on their proboscis; no alternative pollinators are known. The Asparagaceae family comprises about 40 species with night-blooming flowers that are specifically pollinated by *Tegeticula* and *Parategeticula* moths (Prodoxidae), which carry pollen on axillary tentacle structures near the proboscis, with no other pollinators involved. In the Cactaceae, *Lophocereus*

schottii also exhibits nocturnal flowering and is pollinated by the moth *Upiga virescens* (Pyralidae), which transfers pollen using specialized abdominal brushes; however, unlike the other two families, it also has alternate pollinators such as halictid bees.

Conclusion

Bees are important pollinators, but moths can often pollinate flowers at a faster rate than diurnal insects. These nectar-feeding moths play a significant role in pollination and contribute notably to the pollination of several agricultural crops such as apple, avocado, and gourds. However, agro-ecosystems are not composed only of crop plants; they also include field margins, hedgerows, meadows, and other semi-natural habitats that support a wide diversity of non-crop plant species. In these systems, moths act as important co-pollinators of wild flora within agricultural landscapes. Maintaining moth populations and their habitats is essential for ecosystem health, as they also function as ecological indicators. Nevertheless, the ecological interactions and trade-offs involving moths in pollination systems are still poorly understood and require further research.

References

1. Buxton, M. N., Gaskett, A. C., Lord, J. M., & Pattemore, D. E. (2022). A global review demonstrating the importance of nocturnal pollinators for crop plants. *Journal of Applied Ecology, 59*(12), 2890–2901.
2. Faheem, M., Aslam, M., & Razaq, M. (2004). Pollination ecology with special reference to insects: A review. *Journal of Research (Science), 15*(4), 395–409.
3. Fijen, T. P. M., Roovers, A., Deijk, J. V., & Grunsven, R. H. A. (2023). Nocturnal pollination is equally important as and complementary to diurnal pollination for strawberry fruit production. *Agriculture, Ecosystems and Environment, 350*, 108475. https://doi.org/10.1016/j.agee.2023.108475
4. Hahn, M., & Bruhl, C. A. (2016). The secret pollinators: An overview of moth pollination with a focus on Europe and North America. *Arthropod-Plant Interactions, 10*(1), 21–28.
5. Hansson, B. S. (1995). Olfaction in Lepidoptera. *Experientia, 51*, 1003–1027.
6. Jurgens, A., Witt, T., & Gottsberger, G. (2002). Flower scent composition in night-flowering *Silene* species (Caryophyllaceae). *Biochemical Systematics and Ecology, 30*, 383–397.
7. Macgregor, C. J., & Scott-Brown, A. S. (2020). Nocturnal pollination: An overlooked ecosystem service vulnerable to environmental change. *Emerging Topics in Life Sciences, 4*, 19–32.
8. Macgregor, C. J., Pocock, M. J. O., Fox, R., & Evans, D. M. (2015). Pollination by nocturnal Lepidoptera and the effects of light pollution: A review. *Ecological Entomology, 40*, 187–198.

9. Ollerton, J., Winfree, R., & Tarrant, S. (2011). How many flowering plants are pollinated by animals? *Oikos, 120*, 321–326.
10. Ortega-Baes, P., Saravia, M., Suhring, S., Godinez-Alvarez, H., & Zamar, M. (2010). Reproductive biology of *Echinopsis terscheckii* (Cactaceae): The role of nocturnal and diurnal pollinators. *Plant Biology, 13*(1), 33–40.
11. Pansarin, E. R., & Pansarin, L. M. (2017). Crane flies and microlepidoptera also function as pollinators in *Epidendrum* (Orchidaceae: Laeliinae): The reproductive biology of *E. avicula*. *Plant Species Biology, 32*, 200–209.
12. Ribas Marques, E., Diaz Calafat, J., & Boi, M. (2020). The role of adult noctuid moths (Lepidoptera: Noctuidae) and their food plants in a nocturnal pollen transport network on a Mediterranean island. *Journal of Insect Conservation, 26*, 243–255.
13. Singh, N., Lenka, R., Chatterjee, P., & Mitra, D. (2022). Settling moths are the vital component of pollination in Himalayan ecosystem of North East India, pollen transfer network approach revealed. *Scientific Reports, 12*(1), 2716.
14. Subhakar, G., & Sreedevi, K. (2015). Nocturnal insect pollinator diversity in bottle gourd and ridge gourd in southern Andhra Pradesh. *Current Biotica, 9*(2), 137–144.
15. Warrant, E., & Somanathan, H. (2022). Colour vision in nocturnal insects. *Philosophical Transactions of the Royal Society of London B, 377*, 20210285. https://doi.org/10.1098/rstb.2021.0285
16. Young, H. J. (2002). Diurnal and nocturnal pollination of *Silene alba* (Caryophyllaceae). *American Journal of Botany, 89*(3), 433–440.

ANDHRA PRADESH AS A HUB OF SMART AGRICULTURAL INNOVATIONS

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Abstract

Smart agriculture has emerged as an innovative and sustainable approach for addressing the growing challenges faced by the agricultural sector, including climate variability, water scarcity, labour shortages, declining productivity, and inefficient resource utilization. Andhra Pradesh has become one of the leading states in India in adopting smart farming technologies and climate-resilient agricultural practices through the integration of digital technologies, precision agriculture, drone applications, IoT-based systems, artificial intelligence, and smart irrigation techniques. This chapter examines the success stories of smart farming in Andhra Pradesh by analyzing technological interventions, institutional support mechanisms, policy initiatives, and farmer-led innovations across different farming systems. The chapter highlights the role of precision farming, digital advisory services, drone-based crop monitoring, climate-smart agriculture, and Farmer Producer Organizations (FPOs) in improving productivity, profitability, sustainability, and rural livelihoods. It also discusses the economic, social, and environmental impacts of smart agriculture, including improved resource-use efficiency, enhanced water conservation, reduced input costs, increased farm income, and climate resilience. Furthermore, the chapter identifies major challenges such as high investment costs, digital illiteracy, infrastructural limitations, and unequal access to technology that constrain the widespread adoption of smart farming. Finally, the chapter provides policy suggestions and future directions for strengthening digital infrastructure, institutional coordination, inclusive technology access, climate-smart agricultural systems, and agritech innovation ecosystems. The experiences of Andhra Pradesh demonstrate that smart farming can play a significant role in achieving sustainable agricultural transformation and resilient rural development in India.

Keywords: Smart Agriculture, Precision Farming, Internet of Things (IoT), Climate-Smart Agriculture, Drone-Based Crop Monitoring, Digital Advisory Services, Sustainable Agricultural Development.

1. Introduction

Agriculture in India is undergoing a major transformation with the integration of digital technologies, precision farming practices, and climate-smart innovations. In recent years, the

concept of smart farming has emerged as an effective approach to address challenges such as declining farm profitability, labour scarcity, climate variability, water shortages, and inefficient resource utilization. Smart farming refers to the application of advanced technologies such as the Internet of Things (IoT), Artificial Intelligence (AI), drones, remote sensing, Geographic Information Systems (GIS), sensors, automation, and data analytics in agricultural production and management. These technologies help farmers make informed decisions, optimize input use, improve productivity, and ensure environmental sustainability (icar.gov.in).

Andhra Pradesh has emerged as one of the leading states in India in adopting innovative and technology-driven agricultural practices. The state has actively promoted digital agriculture, climate-resilient farming, micro-irrigation systems, and natural farming initiatives to enhance agricultural sustainability and farmers' livelihoods. The increasing adoption of smart irrigation systems, sensor-based technologies, drone applications, mobile advisory services, and precision nutrient management practices has significantly contributed to improving crop productivity and resource-use efficiency in several districts of Andhra Pradesh (The Times of India).

The success of smart farming in Andhra Pradesh is largely supported by government interventions, agricultural universities, research institutions, Farmer Producer Organizations (FPOs), agritech startups, and extension agencies. Institutions such as Indian Council of Agricultural Research and Acharya N. G. Ranga Agricultural University have played a significant role in promoting precision agriculture, climate-smart technologies, and digital advisory systems for farmers. Recent initiatives have focused on strengthening data-driven agriculture through AI-based decision support systems, smart irrigation management, mobile-based advisories, and geospatial technologies (icar.gov.in).

Several progressive farmers and farming communities in Andhra Pradesh have successfully adopted smart farming technologies in crops such as chilli, paddy, fruits, vegetables, and horticultural crops. These success stories demonstrate how modern technologies can reduce production costs, increase yields, improve water-use efficiency, minimize environmental degradation, and strengthen resilience against climate change. Particularly in water-stressed regions, technologies such as drip irrigation, automated fertigation, weather-based crop advisories, and drone-assisted crop monitoring have shown promising outcomes in enhancing farm income and sustainability (ICAR E-Pubs).

Moreover, the integration of digital platforms and mobile applications has improved farmers' access to market information, weather forecasts, pest and disease management practices, and real-time agricultural advisories. Smart agriculture is not only transforming farming practices but also creating opportunities for rural entrepreneurship, agritech innovation, and inclusive agricultural development. The transition from traditional agriculture to data-driven and

intelligent farming systems is expected to play a crucial role in achieving sustainable agricultural growth and food security in the future (ICAR E-Pubs).

This chapter focuses on the success stories of smart farming in Andhra Pradesh by examining various technological interventions, innovative farming practices, institutional support systems, and their socio-economic impacts on farming communities. The chapter also highlights the challenges in technology adoption and provides policy suggestions for scaling up smart agriculture for sustainable rural development.

2. State Agricultural Context

Andhra Pradesh is one of the agriculturally important states in India, with agriculture serving as a major source of livelihood for a significant proportion of the rural population. The state possesses diverse agro-climatic conditions, fertile river basins, extensive irrigation systems, and a strong agricultural infrastructure that supports the cultivation of food grains, commercial crops, horticultural crops, and plantation crops. Major crops grown in the state include paddy, maize, groundnut, cotton, sugarcane, chilli, oil palm, fruits, and vegetables. Agriculture contributes substantially to the state economy and plays a crucial role in employment generation, food security, and rural development. Despite its importance, the agricultural sector faces several challenges such as fragmented landholdings, declining soil fertility, labour shortages, water scarcity, market fluctuations, and climate variability (extensionjournal.com).

The agricultural landscape of Andhra Pradesh is characterized by a predominance of small and marginal farmers who often experience difficulties in adopting advanced technologies due to limited financial resources and inadequate access to institutional support. Regional disparities in irrigation facilities, input utilization, and market access further influence agricultural productivity across districts. Coastal Andhra regions benefit from canal irrigation systems, whereas Rayalaseema districts frequently face drought conditions and water stress. Such climatic and resource-based disparities have increased the need for sustainable and climate-resilient agricultural practices in the state (Indian Journals).

In recent years, Andhra Pradesh has witnessed a gradual transformation from conventional farming practices toward diversified and technology-oriented agriculture. Crop diversification has become increasingly important as farmers shift from traditional cereal crops to high-value horticultural crops, commercial crops, and integrated farming systems to enhance farm income and reduce production risks. Studies indicate that districts such as Kurnool, Prakasam, Kadapa, and Anantapur have shown significant levels of crop diversification due to changing climatic conditions, market demand, and technological interventions. The adoption of micro-irrigation systems, protected cultivation, precision nutrient management, and climate-smart technologies has improved resource-use efficiency and farm productivity in several regions of the state (extensionjournal.com).

The state government has undertaken several initiatives to strengthen sustainable agriculture and digital farming practices. Programs related to micro-irrigation, natural farming, digital extension services, climate-resilient agriculture, and farmer collectivization through Farmer Producer Organizations (FPOs) have gained prominence. Andhra Pradesh has emerged as a leading state in the implementation of micro-irrigation systems, benefiting a large number of farmers through drip and sprinkler irrigation technologies. In addition, the promotion of Andhra Pradesh Community Natural Farming (APCNF) has received national and international recognition for encouraging low-cost, environmentally sustainable farming systems (Reddit).

Climate change has become a major concern for agriculture in Andhra Pradesh due to increasing frequency of droughts, cyclones, floods, and erratic rainfall patterns. Districts in Rayalaseema and north coastal Andhra Pradesh are particularly vulnerable to climatic risks, which affect crop yields, farm income, and rural livelihoods. To address these challenges, climate-resilient agricultural technologies, adaptive farming strategies, and weather-based advisory services are increasingly being promoted through government agencies, research institutions, and extension organizations. The integration of digital agriculture tools, geospatial technologies, artificial intelligence, and data-driven farm management practices is gradually improving the resilience and sustainability of the agricultural sector in Andhra Pradesh (IJRR Journal). Thus, the agricultural context of Andhra Pradesh reflects a dynamic transition toward sustainable, technology-enabled, and climate-smart agriculture. The state's experiences in promoting innovative farming systems, digital technologies, and institutional support mechanisms provide an important foundation for understanding the emergence and success of smart farming practices across different farming communities.

3. Smart Technologies and Practices

Smart agriculture has emerged as a transformative approach that integrates advanced technologies with conventional farming practices to improve agricultural productivity, resource-use efficiency, sustainability, and profitability. The rapid advancement of digital technologies such as Artificial Intelligence (AI), Internet of Things (IoT), drones, remote sensing, big data analytics, robotics, cloud computing, and precision farming tools has significantly reshaped agricultural systems worldwide. In Andhra Pradesh, the adoption of smart technologies is gradually increasing due to rising awareness among farmers, institutional support, government initiatives, and the growing need for climate-resilient and efficient farming systems. These technologies enable real-time monitoring, data-driven decision-making, and precise management of agricultural operations, thereby reducing input wastage and improving crop performance (frontiersin.org).

One of the major components of smart farming is precision agriculture, which involves the application of inputs such as fertilizers, pesticides, and water in precise quantities based on crop

and soil requirements. Precision farming technologies use sensors, GPS-enabled devices, satellite imagery, and Geographic Information Systems (GIS) to monitor field variability and optimize farm operations. In Andhra Pradesh, precision nutrient management and site-specific crop management practices are increasingly being adopted in crops such as chilli, paddy, cotton, and horticultural crops. These practices help farmers minimize production costs, improve nutrient-use efficiency, and increase crop yields while reducing environmental degradation. (mdpi.com)

The Internet of Things (IoT) has become an essential tool in smart farming systems. IoT-based devices such as soil moisture sensors, automated irrigation controllers, weather monitoring stations, and smart fertigation systems provide real-time information about field conditions and crop requirements. Farmers can monitor soil moisture, temperature, humidity, and nutrient levels remotely through mobile applications and cloud-based platforms. Such technologies are particularly beneficial in water-scarce regions of Andhra Pradesh, where efficient irrigation management is crucial for sustainable agriculture. Automated drip irrigation systems integrated with IoT technologies have shown considerable success in improving water-use efficiency and reducing labour dependency. (sciencedirect.com)

Drone technology is another important innovation transforming agricultural practices in Andhra Pradesh. Agricultural drones are widely used for crop monitoring, pesticide spraying, disease detection, nutrient assessment, and field mapping. Drone-based spraying technologies help farmers reduce chemical usage, save time, and improve spraying accuracy compared to traditional methods. Remote sensing technologies and multispectral imaging also assist in early detection of pest infestations, nutrient deficiencies, and crop stress conditions. These technologies provide timely advisories to farmers, enabling preventive measures and minimizing crop losses. The use of drones in precision agriculture is gaining popularity, especially among progressive farmers and Farmer Producer Organizations (FPOs). (nature.com)

Artificial Intelligence and machine learning technologies are increasingly being integrated into agricultural decision-support systems. AI-powered platforms analyze large volumes of agricultural data to provide recommendations on crop selection, irrigation scheduling, pest and disease management, yield prediction, and market intelligence. Mobile-based advisory applications and digital extension platforms are helping farmers access weather forecasts, market prices, and agronomic recommendations in real time. In Andhra Pradesh, digital advisory systems are supporting farmers in making informed decisions related to crop management and risk reduction. The use of big data analytics and AI-based predictive models is expected to further strengthen smart farming systems in the future. (springer.com)

Climate-smart agricultural practices are also an integral part of smart farming technologies. Practices such as conservation agriculture, integrated nutrient management, micro-irrigation, protected cultivation, and climate-resilient crop varieties are increasingly promoted to enhance

sustainability and resilience against climate variability. Andhra Pradesh has gained recognition for promoting sustainable farming initiatives such as natural farming and low-input agriculture. The integration of digital technologies with climate-smart practices has improved farm productivity, reduced environmental risks, and strengthened livelihood security among farming communities. Furthermore, the emergence of agritech startups, digital marketplaces, and e-commerce platforms is creating new opportunities for agricultural modernization and rural entrepreneurship in the state. (fao.org)

Overall, smart technologies and innovative farming practices are playing a crucial role in transforming agriculture in Andhra Pradesh. The increasing adoption of digital tools, automation systems, precision farming methods, and climate-smart practices demonstrates the potential of technology-driven agriculture in achieving sustainable agricultural development, food security, and improved farmer livelihoods.

4. Case Studies / Success Stories

The successful adoption of smart farming technologies in Andhra Pradesh demonstrates how digital innovations, precision agriculture, and climate-smart practices can significantly improve agricultural productivity, profitability, and sustainability. Across different districts of the state, progressive farmers, Farmer Producer Organizations (FPOs), agritech companies, and government agencies have implemented innovative farming models that showcase the practical benefits of smart agriculture. These success stories provide valuable insights into how technology-driven agriculture can address major challenges such as water scarcity, labour shortages, pest infestations, climate variability, and inefficient resource utilization. (The Economic Times)

One of the notable success stories in Andhra Pradesh is the large-scale adoption of micro-irrigation systems under the Andhra Pradesh Micro Irrigation Project (APMIP). Farmers cultivating crops such as chilli, tomato, oil palm, pulses, and horticultural crops have experienced considerable improvements in water-use efficiency, crop yields, and input management through drip and sprinkler irrigation systems. Recent reports indicate that Andhra Pradesh achieved the highest micro-irrigation coverage in India during 2025–26, benefiting more than one lakh farmers across the state. The integration of sensor-based irrigation systems and automated fertigation technologies has enabled farmers to optimize water and fertilizer usage while reducing cultivation costs. These interventions have been especially successful in drought-prone districts such as Anantapur, Kurnool, and Chittoor, where water conservation is critical for sustainable agriculture. (The Times of India)

Another important example of smart farming success is the growing use of drone technology in agriculture. Andhra Pradesh has emerged as a leading state in promoting agricultural drones for crop monitoring, pesticide spraying, nutrient management, and precision farming applications.

The state government has initiated programs to provide drones to farmer groups and FPOs with substantial financial subsidies, thereby improving accessibility among small and marginal farmers. Drone-based spraying technologies have reduced labour dependency, minimized chemical wastage, and improved operational efficiency in crops such as paddy, cotton, and chilli. Pilot projects conducted in oil palm plantations in East Godavari district demonstrated the effectiveness of drones in detecting pest infestations, monitoring crop health, and estimating yields with high accuracy. These technologies have enabled farmers to take timely corrective measures, thereby improving productivity and reducing crop losses. (Metro India)

The use of drones has also demonstrated success beyond crop production activities. During the severe floods in Vijayawada and surrounding districts, Andhra Pradesh effectively utilized drones for relief operations, aerial surveillance, transportation of medicines, and spraying disinfectants in flood-affected areas. The state showcased these applications during the Amaravati Drone Summit 2024, highlighting the broader role of drone technology in disaster management and rural development. Such initiatives have strengthened the technological ecosystem in Andhra Pradesh and encouraged greater acceptance of drone-based agricultural services among farmers and rural entrepreneurs. (The Week)

Women Self-Help Groups (SHGs) have also played a significant role in the adoption of smart farming technologies in Andhra Pradesh. Under the "Namo Drone Didi" initiative, several women SHGs in districts including Guntur received agricultural drones along with operational training to support precision agriculture activities. These initiatives have not only modernized farming operations but also created employment opportunities and entrepreneurial models for rural women. The participation of women in drone-based agricultural services reflects the inclusive potential of smart agriculture in improving rural livelihoods and strengthening community-based agricultural support systems. (Global Agriculture)

Another successful model is the adoption of climate-smart and natural farming practices integrated with digital technologies. Andhra Pradesh has gained recognition for promoting sustainable agricultural systems through natural farming, precision nutrient management, and low-input agriculture. Several farmers have combined weather-based advisories, mobile applications, soil testing technologies, and smart irrigation systems with natural farming practices to reduce production costs and improve soil health. These integrated approaches have increased resilience against climate change and enhanced profitability among farming households. The state's initiatives in combining sustainable farming with digital innovation are increasingly viewed as a model for other regions in India. (The Times of India)

In drought-prone regions of Andhra Pradesh, innovative farmers have demonstrated how smart irrigation and technology-driven farm management can transform unproductive lands into highly profitable agricultural enterprises. Success stories from Rayalaseema highlight the adoption of

precision irrigation systems, automated water management, and scientific crop planning to enhance productivity under water-scarce conditions. Such examples illustrate the importance of integrating local knowledge with modern technologies for sustainable agricultural development. These case studies collectively reveal that smart farming practices have the potential to improve resource efficiency, increase farm income, strengthen climate resilience, and promote sustainable rural transformation in Andhra Pradesh. (The Economic Times)

5. Impacts and Outcomes

The adoption of smart farming technologies and innovative agricultural practices in Andhra Pradesh has generated significant economic, social, environmental, and institutional impacts across the agricultural sector. The integration of precision agriculture, digital advisory systems, drone technologies, climate-smart farming practices, and micro-irrigation systems has contributed to improving agricultural productivity, resource-use efficiency, and farmer livelihoods. These technological interventions are gradually transforming traditional farming systems into data-driven and sustainable agricultural models capable of addressing emerging challenges such as climate variability, labour shortages, and declining natural resources. (sciencedirect.com)

One of the major outcomes of smart farming in Andhra Pradesh has been the improvement in crop productivity and farm income. Precision farming practices such as sensor-based irrigation, soil testing, automated fertigation, and AI-based crop advisory services have enabled farmers to optimize the use of water, fertilizers, and pesticides. As a result, farmers have experienced higher yields, better crop quality, and reduced input costs. Studies indicate that the adoption of precision agriculture technologies can increase crop productivity while reducing wastage of agricultural inputs and minimizing environmental degradation. In crops such as chilli, paddy, horticultural crops, and oil palm, the use of smart irrigation and precision nutrient management practices has improved profitability and enhanced resource-use efficiency among farmers in Andhra Pradesh. (mdpi.com)

Smart irrigation systems and micro-irrigation technologies have produced substantial impacts on water conservation and sustainable resource management. Andhra Pradesh, particularly drought-prone regions such as Rayalaseema, has benefited from drip irrigation, sprinkler systems, and automated irrigation scheduling technologies. These technologies have significantly improved water-use efficiency by delivering water directly to the root zone and minimizing evaporation and runoff losses. Research findings suggest that smart irrigation systems can reduce water consumption while maintaining or enhancing crop productivity. Such improvements are crucial for ensuring sustainable agricultural development under conditions of increasing water scarcity and climate stress. (frontiersin.org)

The adoption of drone technologies and digital monitoring systems has also enhanced farm management efficiency and reduced labour dependency. Drone-based pesticide spraying and crop monitoring technologies have enabled timely detection of pest infestations, nutrient deficiencies, and crop stress conditions. These technologies have improved operational precision, reduced chemical usage, and minimized health risks associated with manual pesticide application. Furthermore, the use of remote sensing, satellite imagery, and Geographic Information Systems (GIS) has strengthened real-time agricultural monitoring and decision-making processes. Such technological advancements have contributed to increased efficiency in agricultural operations and better management of large-scale farming systems. (nature.com)

Smart farming practices have also generated positive social impacts by improving farmers' access to information, extension services, and market opportunities. Mobile-based advisory platforms and digital agricultural services provide real-time information related to weather forecasts, market prices, crop management, pest control, and government schemes. These digital platforms have strengthened farmers' decision-making capacity and reduced information asymmetry in rural areas. In Andhra Pradesh, Farmer Producer Organizations (FPOs), women Self-Help Groups (SHGs), and agritech startups have played an important role in facilitating collective technology adoption, digital literacy, and entrepreneurial development among farming communities. The increasing involvement of rural youth and women in drone operations, digital extension services, and precision agriculture activities has created new employment opportunities and strengthened inclusive rural development. (fao.org)

Environmental sustainability is another important outcome associated with smart agriculture in Andhra Pradesh. The adoption of climate-smart technologies, conservation agriculture, precision nutrient management, and natural farming practices has contributed to reducing excessive chemical usage, improving soil health, conserving biodiversity, and lowering greenhouse gas emissions. Digital technologies support efficient resource utilization and enable farmers to adopt environmentally sustainable agricultural practices. The integration of weather-based advisory systems and climate-resilient farming strategies has improved the adaptive capacity of farmers against climate-related risks such as droughts, floods, and erratic rainfall patterns. These outcomes are particularly important for ensuring long-term agricultural sustainability and food security in the state. (springer.com)

Institutionally, smart farming initiatives have strengthened collaboration among government agencies, agricultural universities, research organizations, private agritech companies, and rural institutions. Policy support, financial assistance, training programs, and digital infrastructure development have accelerated the adoption of smart technologies across different farming systems. Andhra Pradesh's experiences demonstrate that effective institutional coordination and farmer-centric technological interventions can significantly improve the scalability and

sustainability of smart agriculture initiatives. The state's success stories provide valuable lessons for promoting technology-enabled agricultural transformation in other regions of India. (worldbank.org)

Overall, the impacts and outcomes of smart farming in Andhra Pradesh highlight the transformative potential of digital agriculture in enhancing productivity, sustainability, climate resilience, and rural livelihoods. While challenges related to affordability, digital literacy, and infrastructure remain, the positive outcomes achieved through smart technologies indicate strong potential for scaling up sustainable and technology-driven agricultural systems in the future.

6. Challenges and Constraints

Despite the growing adoption of smart farming technologies in Andhra Pradesh, several challenges and constraints continue to limit their widespread implementation and long-term sustainability. Smart agriculture requires the integration of advanced technologies, digital infrastructure, financial investments, institutional support, and technical knowledge, which are not uniformly available across farming communities. The majority of farmers in Andhra Pradesh are small and marginal farmers with limited landholdings, inadequate capital resources, and restricted access to modern technologies. These structural limitations often hinder the adoption of precision farming tools, automated irrigation systems, drones, and digital agricultural platforms. Consequently, the benefits of smart farming are unevenly distributed among different categories of farmers and regions within the state. (mdpi.com)

One of the major constraints in smart farming adoption is the high initial investment required for purchasing advanced technologies and infrastructure. Precision agriculture equipment, IoT devices, drone technologies, automated irrigation systems, and digital monitoring tools involve significant installation and maintenance costs that are often beyond the financial capacity of small-scale farmers. Although government subsidies and institutional support programs are available, many farmers still face difficulties in accessing credit facilities, insurance services, and financial assistance for technology adoption. The lack of affordable and customized smart farming solutions further limits technology penetration in rural areas. (sciencedirect.com)

Digital literacy and technical knowledge among farmers also remain important barriers to the effective use of smart agricultural technologies. Many farmers, particularly elderly farmers and those in remote villages, have limited familiarity with digital tools, mobile applications, sensor technologies, and data-based decision-making systems. The successful operation of precision farming technologies requires technical training, awareness, and continuous advisory support. Inadequate extension services and insufficient technical guidance often reduce farmers' confidence in adopting advanced technologies. Furthermore, language barriers and lack of user-friendly digital interfaces can restrict the accessibility of agricultural advisory platforms among rural populations. (frontiersin.org)

Infrastructure-related limitations also pose serious challenges for smart agriculture development in Andhra Pradesh. Reliable internet connectivity, electricity supply, cloud-based data systems, and digital communication networks are essential for the effective functioning of smart farming technologies. However, several rural areas continue to experience poor network coverage, unstable electricity supply, and inadequate digital infrastructure. These deficiencies affect the performance of IoT devices, real-time monitoring systems, and mobile-based advisory services. The digital divide between urban and rural regions further restricts the large-scale implementation of technology-enabled farming systems. (worldbank.org)

Climate variability and environmental uncertainties also create constraints for smart farming systems. Andhra Pradesh is highly vulnerable to droughts, cyclones, floods, heat waves, and erratic rainfall patterns, which affect crop productivity and technological efficiency. Although smart technologies improve climate resilience, unpredictable weather events can still damage infrastructure, disrupt digital communication systems, and increase production risks. In drought-prone regions such as Rayalaseema, limited groundwater availability and declining water tables further complicate the adoption of water-intensive technologies and irrigation systems. In addition, changing pest and disease patterns associated with climate change require continuous technological adaptation and monitoring. (springer.com)

Data privacy, cybersecurity, and data ownership issues are emerging concerns in digital agriculture. Smart farming systems collect large amounts of farm-level data related to soil conditions, crop management, weather patterns, and production practices. The absence of clear policies regarding data governance, data sharing, and digital security may expose farmers to risks associated with misuse of information, cyber threats, and unequal control over agricultural data. Farmers often have limited awareness regarding data protection and digital rights, making them vulnerable within digital agricultural ecosystems. These concerns highlight the need for transparent regulatory frameworks and ethical guidelines for digital agriculture implementation. (oecd.org)

Institutional and policy-related constraints also affect the successful implementation of smart farming initiatives. Fragmented institutional coordination, limited public-private partnerships, and insufficient integration between research institutions, extension agencies, and agritech companies reduce the efficiency of technology dissemination. Many pilot projects and smart agriculture initiatives remain localized and fail to achieve large-scale adoption due to inadequate follow-up support, monitoring, and capacity-building programs. Furthermore, the absence of location-specific technologies and customized advisory systems often reduces the relevance of digital solutions for diverse agro-climatic conditions in Andhra Pradesh. (fao.org)

Another important challenge is the socio-economic inequality in technology access. Large farmers and commercially oriented agricultural enterprises are more capable of adopting

advanced technologies compared to smallholders, tenant farmers, and resource-poor households. Gender disparities also exist in access to digital tools, training opportunities, and financial support. Women farmers frequently face greater barriers in technology adoption due to limited access to assets, digital education, and institutional resources. Therefore, inclusive and equitable policy interventions are essential to ensure that the benefits of smart agriculture reach all categories of farmers and rural communities. (ifad.org)

Overall, while smart farming offers significant opportunities for improving agricultural sustainability and productivity in Andhra Pradesh, multiple technological, financial, infrastructural, institutional, and socio-economic challenges continue to constrain its effective implementation. Addressing these barriers through targeted policy support, digital infrastructure development, farmer training, affordable technologies, and inclusive institutional frameworks is essential for ensuring the long-term success and scalability of smart agriculture in the state.

7. Policy Suggestions and Future Directions

The successful implementation of smart farming in Andhra Pradesh highlights the transformative potential of digital technologies, precision agriculture, and climate-smart practices in achieving sustainable agricultural development. However, the long-term success and large-scale adoption of smart agriculture require strong policy support, institutional coordination, technological accessibility, and inclusive development strategies. Policymakers, research institutions, private agritech companies, Farmer Producer Organizations (FPOs), and extension agencies must work collaboratively to create an enabling ecosystem that supports innovation, affordability, sustainability, and equitable access to smart farming technologies. Effective policy interventions are essential to ensure that technological advancements benefit all categories of farmers, particularly small and marginal farmers who constitute the majority of the agricultural population in Andhra Pradesh. (worldbank.org)

One of the key policy priorities should be strengthening digital infrastructure in rural areas. Reliable internet connectivity, electricity supply, cloud computing facilities, and mobile communication networks are fundamental requirements for the effective implementation of smart farming technologies. Expanding rural broadband networks and improving digital infrastructure can significantly enhance farmers' access to digital advisory services, online marketplaces, weather forecasting systems, and precision agriculture tools. Government initiatives focusing on rural digital transformation and smart village development can create favourable conditions for scaling digital agriculture across diverse agro-climatic regions of Andhra Pradesh. (itu.int)

Affordable access to smart farming technologies is another critical area requiring policy attention. The high cost of drones, IoT devices, automated irrigation systems, sensors, and precision farming equipment often restricts adoption among smallholder farmers. Therefore,

governments should expand subsidy programs, low-interest agricultural credit schemes, insurance coverage, and public financing mechanisms for technology adoption. Establishing community-based technology centres, custom hiring centres, and shared service platforms through Farmer Producer Organizations (FPOs) can improve access to advanced technologies at lower costs. Such collective models can help reduce financial burdens on individual farmers while promoting efficient utilization of smart agricultural tools. (fao.org)

Capacity building and digital literacy programs are essential for increasing farmers' confidence and technical competence in using smart farming technologies. Continuous training programs, field demonstrations, farmer field schools, and digital extension services should be strengthened to enhance awareness regarding precision farming, drone operations, sensor technologies, data management, and climate-smart practices. Agricultural universities, Krishi Vigyan Kendras (KVKs), research institutions, and extension agencies should play an active role in providing location-specific technical guidance and skill development programs. Special attention should be given to women farmers, rural youth, and socially disadvantaged groups to ensure inclusive participation in digital agriculture initiatives. (ifad.org)

Future agricultural policies should also emphasize climate-resilient and environmentally sustainable farming systems. Andhra Pradesh is highly vulnerable to droughts, floods, cyclones, and changing rainfall patterns, making climate-smart agriculture a policy necessity. Promoting water-efficient technologies such as drip irrigation, automated irrigation systems, rainwater harvesting, and precision nutrient management can improve resource conservation and climate resilience. Similarly, integrating smart technologies with natural farming, organic farming, conservation agriculture, and sustainable land management practices can support long-term environmental sustainability while maintaining agricultural productivity. Policies encouraging renewable energy use, carbon-smart agriculture, and sustainable resource management can further strengthen green agricultural transformation in the state. (unep.org)

Data governance and digital security frameworks are becoming increasingly important in the era of digital agriculture. Smart farming systems generate large volumes of farm-level data related to soil conditions, weather patterns, crop management, and production systems. Therefore, governments should establish transparent policies regarding data ownership, privacy protection, cybersecurity, and ethical use of agricultural data. Clear regulatory frameworks are needed to protect farmers' digital rights while encouraging responsible data sharing and technological innovation. Strengthening institutional mechanisms for digital governance can improve farmers' trust and participation in smart agriculture ecosystems. (oecd.org)

Public–private partnerships (PPPs) and agritech entrepreneurship can play a major role in accelerating agricultural innovation and technology dissemination. Encouraging collaboration between government agencies, agricultural universities, startup companies, financial institutions,

and technology providers can facilitate the development of affordable and scalable agricultural solutions. Andhra Pradesh has significant potential to become a hub for agritech innovation through investments in agricultural incubation centres, digital startups, precision farming enterprises, and rural innovation ecosystems. Supporting youth entrepreneurship in drone services, smart irrigation management, agricultural analytics, and digital extension services can generate employment opportunities and strengthen rural economic development. (niti.gov.in)

Future research and policy directions should focus on developing location-specific and farmer-centric smart farming solutions. Technologies must be adapted to the socio-economic conditions, cropping systems, and agro-climatic realities of different districts in Andhra Pradesh. Research institutions should prioritize interdisciplinary studies on artificial intelligence, machine learning, remote sensing, robotics, and climate modelling for agriculture. Greater emphasis should also be placed on integrating indigenous knowledge systems with modern technologies to create sustainable and culturally appropriate farming models. Long-term monitoring and impact assessment studies are necessary to evaluate the economic, social, and environmental outcomes of smart farming interventions. (cgiar.org)

Overall, the future of smart farming in Andhra Pradesh depends on the development of inclusive, affordable, sustainable, and technology-driven agricultural systems supported by strong policy frameworks and institutional coordination. With appropriate investments in digital infrastructure, farmer capacity building, climate-smart technologies, and innovation ecosystems, Andhra Pradesh can emerge as a leading model for sustainable smart agriculture in India. The experiences and lessons from the state provide valuable guidance for promoting resilient, efficient, and digitally empowered agricultural systems in other developing regions.

Conclusion

The experiences of Andhra Pradesh clearly demonstrate the transformative potential of smart farming technologies in improving agricultural productivity, sustainability, climate resilience, and rural livelihoods. The integration of precision agriculture, IoT-based systems, drone technologies, artificial intelligence, digital advisory platforms, and climate-smart practices has enabled farmers to optimize resource utilization, reduce production costs, and enhance farm profitability. Government initiatives, institutional support, Farmer Producer Organizations (FPOs), agritech startups, and extension agencies have collectively contributed to the successful adoption of innovative agricultural practices across different regions of the state.

The chapter highlights several successful case studies that reveal how technology-driven agriculture can effectively address challenges such as water scarcity, labour shortages, pest management, market uncertainties, and climate variability. Smart irrigation systems, automated fertigation, drone-assisted crop monitoring, and mobile-based advisory services have significantly improved decision-making efficiency and resource conservation among farming

communities. In addition, the promotion of natural farming and climate-resilient agricultural practices has strengthened environmental sustainability and enhanced farmers' adaptive capacity under changing climatic conditions.

Despite these achievements, several challenges continue to limit the large-scale adoption of smart farming technologies in Andhra Pradesh. High initial investment costs, limited digital literacy, inadequate rural infrastructure, poor internet connectivity, data governance concerns, and unequal access to technology remain major barriers, particularly for small and marginal farmers. Therefore, strengthening rural digital infrastructure, improving farmer training and extension services, enhancing institutional coordination, and expanding affordable access to smart technologies are essential for ensuring inclusive and sustainable agricultural development.

Future policy interventions should focus on promoting farmer-centric, location-specific, and climate-resilient smart farming solutions through stronger public–private partnerships, agritech innovation ecosystems, and digital governance frameworks. Greater emphasis on women's participation, youth entrepreneurship, and collective technology adoption through FPOs can further strengthen rural transformation and inclusive growth. Overall, Andhra Pradesh provides an important model for the successful integration of smart technologies into agriculture and offers valuable lessons for scaling sustainable and technology-driven farming systems in other regions of India and developing countries.

References

1. AgriInsite. (2025). *3F Oil Palm expands precision farming with drones in Andhra Pradesh*.
2. Ahmed, S., Kumar, P., & Verma, R. (2024). Drone-based crop monitoring and precision agriculture applications for sustainable farming. *Scientific Reports, 14*, 65278.
3. Alotaibi, B., Rahman, M., & Khan, S. (2024). Digital literacy and technology acceptance in smart agriculture systems. *Frontiers in Sustainable Food Systems, 8*, 1382146.
4. Bohidar, S., & Senapati, A. K. (2025). Assessing agricultural vulnerability to climate extremes in Rayalaseema and KBKK regions of India: A panel ARDL approach. *Discover Agriculture, 3*, 79.
5. *Business Standard*. (2024). *Coromandel International delivers 200 drones to women SHGs to modernise farming*.
6. Devulapalli, R. (2024). Andhra Pradesh showcases drone technology during recent floods as a success story.
7. Elbeltagi, A., Deng, J., Wang, K., Malik, A., & Maroufpoor, S. (2024). Precision agriculture technologies for sustainable crop production and environmental management. *Agriculture, 14*(3), 391.

8. FAO, CIRAD, & RySS. (2024). *Re-thinking food systems in Andhra Pradesh, India: How natural farming could feed the future*. Food and Agriculture Organization.
9. Food and Agriculture Organization (FAO). (2024). *Digital agriculture and inclusive rural innovation in Asia and the Pacific*. FAO Regional Office for Asia and the Pacific.
10. Food and Agriculture Organization (FAO). (2024). *Digital technologies and inclusive rural transformation in Asia and the Pacific*. FAO Regional Office for Asia and the Pacific.
11. Food and Agriculture Organization (FAO). (2024). *Scaling digital agriculture for smallholder farmers in Asia and the Pacific*. FAO Regional Office for Asia and the Pacific.
12. Government of Andhra Pradesh. (2025). *Andhra Pradesh Micro Irrigation Project achieves highest national coverage*. *Times of India, Vijayawada Edition*.
13. Government of India, Ministry of Agriculture & Farmers Welfare. (2025). *Climate-resilient agriculture technologies*. Press Information Bureau.
14. Indian Council of Agricultural Research (ICAR). (2024). *Technical report on revolutionizing agriculture: The digital transformation of farming*.
15. International Telecommunication Union (ITU). (2024). *Smart villages and rural digital infrastructure for sustainable development*. ITU Publications.
16. Javaid, M., Haleem, A., Singh, R. P., & Khan, S. (2024). Towards sustainable smart farming through Internet of Things and Artificial Intelligence: A review. *Frontiers in Sustainable Food Systems, 8*, 1361257.
17. Kour, D., Yadav, A. N., & Kaur, T. (2024). Precision agriculture technologies for improving crop productivity and sustainability. *Agriculture, 14*(5), 705.
18. Kulatunga, C., Dhelim, S., & Kechadi, T. (2024). Machine learning for dynamic management zone in smart farming. *arXiv Preprint*, arXiv:2408.00789.
19. Kumar, R., Singh, P., & Sharma, A. (2024). Barriers to adoption of smart agriculture technologies among smallholder farmers. *Sustainability, 16*(5), 1932.
20. Li, M., Zhang, Y., & Wang, J. (2024). Smart irrigation systems for water-efficient agriculture under climate change. *Frontiers in Sustainable Food Systems, 8*, 1378295.
21. *Metro India News*. (2025). *AP Govt to provide drones to farmers with 80% subsidy*.
22. Mishra, B., & Reddy, M. S. (2024). Implementation and impact of climate resilient zero-budget natural farming: A case study of Andhra Pradesh Community Natural Farming in Anantapuramu district. *IASSI Quarterly, 43*(4), 878–891.
23. Naik, M. R., Apparao, C., Neelima, T. L., Teja, R. R., Singh, T., & Ramanjaneyulu, A. (2025). Digital agriculture and data-driven farming solutions for sustainable development. *Indian Farming, 75*(12), 84–87.

24. NITI Aayog. (2024). *Agritech innovation ecosystem in India: Opportunities and future pathways*. Government of India.
25. OECD. (2024). *Artificial intelligence in agriculture: Policy implications and governance frameworks*. OECD Publishing.
26. OECD. (2024). *Digital agriculture and data governance: Policies for sustainable farming*. Organisation for Economic Co-operation and Development.
27. Rane, N., Choudhary, S., & Sinha, P. (2024). Smart agriculture technologies and their impact on sustainable farming systems. *Smart Agricultural Technology, 8*, 100512.
28. Sharma, N., Gupta, M., & Verma, P. (2024). Artificial intelligence and machine learning applications in smart agriculture: Opportunities and challenges. *Artificial Intelligence Review, 57*, 198.
29. Singh, P., Sharma, A., & Kumar, R. (2024). IoT-enabled smart irrigation systems for sustainable agriculture: Recent advances and applications. *Smart Agricultural Technology, 8*, 100488.
30. Sreenivasulu, S., Sudhakar, P. S., Divya, V., Kumar, T. R., Prasad, J. V., & Meera, S. N. (2024). Impact of climate resilient technologies in Chittoor district of Andhra Pradesh. *Indian Farming, 74*(3), 65–67.
31. Tanuja, N., Ravi Kumar, K. N., Rama Rao, I. V. Y., & Suseela, K. (2024). Dynamics of crop diversification in Andhra Pradesh: A district-level analysis. *International Journal of Agriculture Extension and Social Development, 7*(12S), 33–37. https://doi.org/10.33545/26180723.2024.v7.i12Sa.1445
32. Tarate, S. B., Patel, N. R., Danodia, A., Pokhariyal, S., & Parida, B. R. (2024). Geospatial technology for sustainable agricultural water management in India—A systematic review. *Geomatics, 4*(2), 91–123.
33. Verma, S., Patel, N., & Gupta, R. (2024). Economic and infrastructural constraints in smart farming adoption. *Smart Agricultural Technology, 8*, 100573.
34. World Bank. (2024). *Harvesting opportunities: Digital agriculture and rural transformation in India*. World Bank Publications.
35. Yadav, V., Choudhary, R., & Pradhan, P. (2024). Applications of drone technology in precision agriculture and crop monitoring. *Scientific Reports, 14*, 56342.

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ARTIFICIAL INTELLIGENCE IN INDIAN AGRICULTURE: ADOPTION, CHALLENGES, AND THE ROAD AHEAD

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Abstract

The Indian agricultural sector, which sustains more than half the national population, is undergoing a significant technological transformation driven by artificial intelligence (AI). This paper examines the current state of AI adoption across Indian agriculture, encompassing precision farming, crop disease diagnostics, weather forecasting, market price prediction, and supply chain optimization. Drawing on secondary data and recent empirical studies, the analysis maps adoption patterns across different farm sizes and geographies, identifies structural and socio-economic barriers, and evaluates the roles played by government policy and private-sector innovation. The findings indicate that while AI-driven tools demonstrate measurable productivity gains—including yield improvements of up to 30 percent and reductions in input wastage—widespread diffusion remains constrained by limited digital infrastructure, low farmer digital literacy, fragmented landholdings, and data scarcity. The paper argues that bridging the gap between technological potential and ground-level adoption requires coordinated investment in rural connectivity, localized AI applications, inclusive training programmes, and farmer-centric policy frameworks. Targeted interventions in these areas could position AI as a cornerstone of sustainable and inclusive agricultural development in India.

Keywords: Artificial Intelligence, Indian Agriculture, Precision Farming, Digital Transformation, Agri-tech, Smart Farming.

1. Introduction

Agriculture remains the backbone of the Indian economy, contributing approximately 18 percent to gross domestic product and providing livelihoods to nearly 54 percent of the workforce (Ministry of Agriculture, Government of India, 2023). Yet the sector faces mounting pressures: erratic monsoons, soil degradation, post-harvest losses estimated at 15–20 percent of produce, volatile market prices, and the long-term challenge of feeding a population projected to exceed 1.5 billion by 2030. Against this backdrop, artificial intelligence has emerged as a potentially transformative force.

AI encompasses a suite of technologies—machine learning, computer vision, natural language processing, and predictive analytics—that can process vast datasets to generate actionable insights. In agriculture, these capabilities translate into tools that help farmers decide when to

sow, how much to irrigate, which pest threats are approaching, and at what price to sell. The promise is substantial: the Indian Council of Agricultural Research (ICAR) estimates that AI-enabled precision agriculture could add USD 15–20 billion to farm incomes annually by 2030.

However, enthusiasm for AI in agriculture must be tempered by realism about structural constraints. India's agricultural landscape is characterised by an average farm holding of barely 1.1 hectares, low broadband penetration in rural areas, limited institutional credit access, and a wide digital literacy gap. These factors complicate the straightforward transfer of technologies developed in data-rich, large-farm environments in the United States or Europe.

This paper seeks to provide a nuanced account of where AI adoption stands in Indian agriculture, what is driving it, what is holding it back, and what policy and practice interventions are most likely to accelerate inclusive and sustainable adoption. The paper is structured as follows: Section 2 reviews the existing literature; Section 3 discusses the AI applications currently in use; Section 4 analyses adoption patterns; Section 5 examines barriers; Section 6 evaluates policy and market initiatives; Section 7 discusses future directions; and Section 8 concludes.

2. Review of Literature

Scholarly interest in digital agriculture and AI has grown considerably over the past decade. Wolfert *et al.* (2017) provided an early conceptualisation of big data in smart farming, highlighting the potential for data-driven decision support systems to optimise resource use across the agricultural value chain. Their framework remains influential in understanding how AI fits into broader agri-tech ecosystems.

Within the Indian context, Birthal and Hazrana (2019) documented the productivity dividends associated with technology adoption in smallholder farming, though they cautioned that gains are often unevenly distributed along socio-economic lines. Singh *et al.* (2020) examined the use of remote sensing and machine learning for crop yield estimation in Punjab and Haryana, reporting prediction accuracies exceeding 85 percent, but also identifying the high cost of satellite data as a bottleneck.

Research by Khatri-Chhetri *et al.* (2017) on climate-smart agriculture in South Asia underscored the critical role of advisory services and information and communication technology in helping farmers adapt to climate variability. Their findings align with subsequent work by Pathak *et al.* (2021), who evaluated AI-based weather advisory systems and found that farmers who received AI-generated agrometeorological advisories reduced weather-related crop losses by an average of 22 percent compared to a control group.

The barriers to adoption have also attracted scholarly attention. Aker (2011) demonstrated that mobile information services improve agricultural market efficiency, but underscored that low digital literacy limits uptake among marginalised communities. More recently, Raina *et al.* (2023) conducted a survey of 1,200 smallholder farmers in five Indian states and found that

fewer than 12 percent used any AI-driven application, with internet connectivity and awareness cited as the primary obstacles. Their study also found a positive correlation between adoption and proximity to urban agri-markets, suggesting that geography shapes access to innovation.

The literature converges on a set of enabling conditions for successful AI adoption: reliable connectivity, appropriate and affordable devices, locally relevant content, trusted intermediaries, and policy environments that incentivise data sharing and innovation. The present paper builds on these foundations to assess the current Indian landscape comprehensively.

3. AI Applications in Indian Agriculture

The deployment of AI in Indian agriculture spans several domains, each addressing distinct pain points in the farming system.

3.1 Precision Farming and Crop Management

Precision farming leverages sensors, drones, satellite imagery, and AI algorithms to monitor soil health, moisture levels, and crop growth at granular spatial scales. Startups such as CropIn, Fasal, and DeHaat have developed platforms that integrate field-level data with predictive models to generate personalised agronomic advisories. CropIn's SmartFarm platform, for instance, serves over 7 million acres across India, providing crop-specific recommendations that farmers report have helped reduce input costs by 15–25 percent while improving yields.

Drone-based applications are also gaining ground. Agri companies including Garuda Aerospace and IoTechWorld Avigen deploy autonomous drones for crop surveillance and targeted pesticide spraying, claiming reductions in chemical use of up to 30 percent compared to conventional broadcast spraying. The government's Kisan Drone initiative, launched in 2022, has accelerated drone adoption by offering purchase subsidies of up to 50 percent to farmer cooperatives.

3.2 Crop Disease and Pest Detection

Computer vision models trained on large annotated image datasets can identify plant diseases and pest infestations from smartphone photographs with high accuracy. The Plantix application, developed by PEAT GmbH but widely used in India, uses deep learning to diagnose over 400 plant diseases across 60 crops and provides treatment recommendations in multiple Indian languages. Studies have reported diagnostic accuracy of 85–92 percent when tested against expert agronomist assessments.

ICAR and state agricultural universities have been building India-specific datasets to train localised models better suited to domestic crop varieties and agro-climatic conditions. The National e-Governance Plan in Agriculture (NeGP-A) provides institutional support for such data infrastructure projects.

3.3 Weather Forecasting and Climate Advisory

Accurate, hyper-local weather forecasting is critical for sowing and harvesting decisions. The India Meteorological Department (IMD) has integrated machine learning algorithms into its

numerical weather prediction models, improving forecast precision for short-range (1–3 day) predictions. Private players such as SkyMet and aWhere provide subscription-based agrometeorological advisories that leverage AI to generate field-level forecasts.

The Digital Green initiative has demonstrated that farmers who receive AI-generated weather and crop management videos via rural community networks show measurable improvements in practice adoption compared to those receiving conventional extension services. This finding is significant because it suggests AI can augment, rather than replace, existing extension infrastructure.

3.4 Market Price Prediction and Trading Support

Price volatility is a chronic source of income insecurity for Indian farmers. AI-driven price forecasting models, which integrate historical mandi (wholesale market) data, crop production estimates, weather patterns, and macroeconomic indicators, can provide farmers and traders with price outlook information. The government's Agmarket and e-NAM (National Agriculture Market) platforms use predictive analytics to help farmers decide when and where to sell.

Research by Kumar and Sharma (2022) on price forecasting for tomatoes in Maharashtra found that LSTM (Long Short-Term Memory) neural networks outperformed traditional ARIMA models in predicting weekly mandi prices, achieving a mean absolute percentage error of 8.3 percent versus 14.7 percent. Such accuracy improvements, if reliably disseminated to farmers, could materially reduce the risk of distress selling.

3.5 Supply Chain Optimisation and Post-Harvest Management

Post-harvest losses in Indian agriculture, particularly for fruits and vegetables, represent a significant economic and nutritional drain. AI applications are increasingly being applied to cold chain management, logistics routing, quality grading, and demand forecasting. Companies such as Ninjacart and Waycool use AI-based demand planning to reduce wastage in their supply chains, claiming reductions of 20–25 percent in spoilage rates.

RFID-enabled smart warehouses and AI-driven quality grading systems are being piloted under the Pradhan Mantri Kisan Sampada Yojana, with early results indicating that automated quality assessment reduces grading time by 60 percent and improves price realisation for farmers by 8–12 percent by enabling better market segmentation.

4. Patterns of AI Adoption Across Indian Agriculture

Adoption of AI in Indian agriculture is deeply uneven across geographic, demographic, and farm-size dimensions. Large commercial farms in irrigated, high-value crop belts—such as the grape and pomegranate belts of Maharashtra, the basmati rice regions of Punjab and Haryana, and the polyhouse horticulture clusters of Himachal Pradesh—exhibit comparatively high technology uptake. These farms typically have access to institutional credit, educated farm managers, established market linkages, and proximity to agri-tech service providers.

In contrast, smallholder and marginal farmers—who constitute approximately 86 percent of all agricultural holdings in India—remain largely outside the AI adoption frontier. A national-level survey by NABARD (2023) found that smartphone ownership among agricultural households has risen to 62 percent, yet fewer than 14 percent of farmers use agriculture-specific applications. Of those, a fraction use tools that could be classified as AI-driven.

Regional disparities are pronounced. Southern states—particularly Karnataka, Andhra Pradesh, and Tamil Nadu—and the western state of Maharashtra lead in agri-tech adoption, partly because of stronger startup ecosystems and state-level digital agriculture programmes. By contrast, the heavily populated and agriculturally critical states of Bihar, Jharkhand, Uttar Pradesh, and Odisha lag significantly in adoption metrics.

Gender is also a significant dimension. Women constitute approximately 42 percent of India's agricultural workforce but own fewer than 13 percent of operational farm holdings (Food and Agriculture Organization, 2022). Their access to smartphones, digital financial services, and extension education is systematically lower than that of male counterparts, rendering gender-blind technology programmes structurally exclusionary.

5. Barriers to Widespread AI Adoption

A range of interconnected barriers impedes the scaling of AI adoption in Indian agriculture. These can be organised into infrastructure, economic, human capital, and institutional categories.

5.1 Digital Infrastructure Deficits

While India has made impressive strides in mobile connectivity under the BharatNet and Digital India programmes, rural broadband remains unreliable and expensive in many agricultural regions. A 2023 Telecom Regulatory Authority of India (TRAI) report indicated that rural internet penetration stood at 37 percent, compared to 67 percent in urban areas. Low bandwidth limits the use of data-intensive applications such as satellite imagery analysis and video advisory content.

5.2 Economic Constraints

The majority of Indian smallholder farmers operate on thin margins and face persistent income volatility. Many cannot afford subscription fees for AI platforms or invest in hardware such as soil sensors and drones. Even where subsidies exist, the upfront cost and maintenance complexity of precision farming equipment deter adoption. Credit access for technology investment remains limited, particularly for informal and semi-formal farmers not covered by institutional banking.

5.3 Digital Literacy and Trust Deficits

Effective use of AI tools requires a minimum threshold of digital literacy that a significant portion of the farming population has not yet reached, particularly among older and less-educated farmers. Beyond literacy, there is a broader issue of trust: many farmers are sceptical of

algorithmic recommendations that contradict traditional knowledge or that they cannot interrogate or understand. Building trust requires sustained engagement, locally credible intermediaries such as extension workers and farmer producer organisations (FPOs), and evidence of tangible outcomes.

5.4 Data Quality and Localisation

AI models are only as good as the data on which they are trained. Much of the existing agricultural AI is built on data from temperate, large-farm environments in North America and Europe, and may not generalise well to the diverse agro-climatic conditions, cropping systems, and local varieties of India. Building India-specific, high-quality, labelled datasets requires sustained investment in data collection infrastructure and inter-institutional data sharing, both of which remain underdeveloped.

5.5 Fragmented Land Holdings and Collective Action Problems

The economics of precision farming typically assume farm sizes at which per-unit technology costs are manageable. On India's average 1.1-hectare holding, the return on investment for most AI-enabled hardware is negative in isolation. Overcoming this challenge requires pooling mechanisms such as FPOs, cooperatives, and shared service centres, but organising smallholder collective action is itself a complex undertaking requiring institutional support.

6. Policy Landscape and Market Interventions

The Government of India has articulated an ambitious vision for digital agriculture through the Digital Agriculture Mission (2021–2025), which envisages building a national farmers' database, creating an agricultural data exchange, and developing an open digital ecosystem for agriculture (AgriStack). The mission explicitly recognises AI as a strategic technology and earmarks resources for AI pilot programmes in partnership with state governments and technology firms.

The PMKSY (Pradhan Mantri Krishi Sinchayee Yojana) and Paramparagat Krishi Vikas Yojana have incorporated AI-assisted irrigation management and organic farming monitoring into their implementation frameworks. The National AI Strategy (NITI Aayog, 2018) identified agriculture as one of five priority sectors for AI investment, and subsequent AI for All initiatives have included agricultural use cases.

On the private side, venture capital investment in Indian agri-tech surged from USD 248 million in 2019 to over USD 1.2 billion in 2022 (AgFunder, 2023), with AI-focused companies attracting a disproportionate share. Large corporates—including Reliance Jio (JioKrishi), Mahindra (Trringo), and ITC (e-Choupal 4.0)—have launched AI-enabled platforms targeting the smallholder segment, leveraging their extensive rural distribution networks.

International development organisations are also active. The Bill and Melinda Gates Foundation, CGIAR, and the World Bank have funded AI for agriculture programmes, often in partnership

with Indian research institutions and state governments. These programmes have generated important evidence on what works and catalysed government adoption of proven approaches.

7. Future Directions and Recommendations

Given the analysis above, several strategic directions merit prioritisation to accelerate inclusive and sustainable AI adoption in Indian agriculture.

First, rural connectivity must be treated as foundational infrastructure. The BharatNet programme should be accelerated and supplemented with satellite-based internet access—through mechanisms such as the OneWeb and Starlink partnerships under negotiation with Indian regulators—to ensure that connectivity gaps do not permanently exclude remote farming communities.

Second, AI tools must be made contextually appropriate. This requires investment in India-specific agricultural datasets, development of AI interfaces in regional languages (India has 22 scheduled languages and hundreds of dialects), and user experience design that accommodates low-literacy users through voice interfaces and visual cues. ICAR, state agricultural universities, and the proposed National Agricultural Research and Education System 2.0 should be co-opted as innovation and validation hubs.

Third, the FPO model deserves particular emphasis as the vehicle for technology diffusion among smallholders. A well-resourced FPO can aggregate demand for technology services, provide collective training, operate shared equipment, and negotiate favourable terms with service providers. Policy should strengthen FPO capacity in digital technology management alongside their commercial functions.

Fourth, data governance frameworks must be designed thoughtfully. As agricultural data collection proliferates, the risk of data exploitation by powerful intermediaries at the expense of farmers grows. The proposed Agriculture Data Management Framework should ensure that farmers have data ownership rights, that data collection is transparent and consensual, and that public-interest data repositories are accessible to researchers and smallholder-focused innovators.

Fifth, capacity building for extension workers and agricultural university graduates in AI literacy should be institutionalised. These professionals are the trusted intermediaries through whom technology reaches the farm gate; their ability to explain, validate, and troubleshoot AI recommendations is critical to adoption and appropriate use.

Conclusion

Artificial intelligence holds genuine transformative potential for Indian agriculture. The evidence from precision farming, disease detection, weather forecasting, price prediction, and supply chain management demonstrates that AI can improve productivity, reduce waste, enhance resilience, and raise farm incomes. These are not trivial gains in a country where agricultural underperformance has profound human consequences.

Yet the technology's transformative promise will remain unrealised at scale unless the deep structural barriers of connectivity, affordability, literacy, data quality, and governance are addressed in parallel with technology development. The risk, as with many prior waves of agricultural technology in India, is that benefits accrue disproportionately to already-advantaged farmers, widening inequality and leaving the most vulnerable further behind.

Realising the inclusive potential of AI in Indian agriculture is not primarily a technical challenge. It is a policy, institutional, and social challenge that requires sustained commitment from government, the private sector, civil society, and the farming community itself. If these actors can coordinate effectively around a shared vision of farmer-centric, data-sovereign, and environmentally sustainable AI adoption, India's agriculture could emerge as a global model of technology-enabled inclusive development.

References

1. AgFunder. (2023). *AgFunder India AgriFoodTech Investment Report*. AgFunder Research.
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. Birthal, P. S., & Hazrana, J. (2019). Crop diversification and resilience of agriculture to climatic shocks: Evidence from India. *Agricultural Systems, 173*, 345–354.
4. Digital India Programme. (2022). *Digital Agriculture Mission 2021–2025: Implementation guidelines*. Ministry of Electronics and Information Technology, Government of India.
5. Food and Agriculture Organization. (2022). *Gendered tenure rights in India: Closing the gap for women farmers*. FAO.
6. India Meteorological Department. (2023). *Annual report 2022–23: Advances in numerical weather prediction*. IMD, Ministry of Earth Sciences.
7. Khatri-Chhetri, A., Aggarwal, P. K., Joshi, P. K., & Vyas, S. (2017). Farmers' prioritisation of climate-smart agriculture (CSA) technologies. *Agricultural Systems, 151*, 184–191.
8. Kumar, R., & Sharma, N. (2022). Forecasting agricultural commodity prices using LSTM neural networks: Evidence from Maharashtra tomato markets. *Journal of Agribusiness in Developing and Emerging Economies, 12*(4), 615–631.
9. Ministry of Agriculture and Farmers' Welfare. (2023). *Agricultural statistics at a glance 2022*. Directorate of Economics and Statistics, Government of India.
10. NABARD. (2023). *NABARD All India Rural Financial Inclusion Survey 2021–22*. National Bank for Agriculture and Rural Development.
11. NITI Aayog. (2018). *National strategy for artificial intelligence #AIForAll*. NITI Aayog, Government of India.

12. Pathak, H., Aggarwal, P. K., & Mahapatra, S. (2021). Agrometeorological advisory services and farmer welfare in climate-vulnerable regions of India. *Weather, Climate and Society, 13*(2), 289–305.
13. Raina, S., Joshi, A., & Pal, S. (2023). Determinants of digital technology adoption among smallholder farmers in India: A multi-state survey. *Indian Journal of Agricultural Economics, 78*(1), 45–67.
14. Singh, A., Ganapathysubramanian, B., Singh, A. K., & Sarkar, S. (2020). Machine learning for high-throughput stress phenotyping in plants. *Trends in Plant Science, 21*(2), 110–124.
15. Telecom Regulatory Authority of India. (2023). *Telecom subscription data report, March 2023*. TRAI.
16. Wolfert, S., Ge, L., Verdouw, C., & Bogaardt, M. J. (2017). Big data in smart farming: A review. *Agricultural Systems, 153*, 69–80.

DESCRIPTIVE PROFILING AND PARAMETRIC TESTS OF SIGNIFICANCE FOR POTATO PRODUCTION IN ODISHA: A COMPARATIVE EMPIRICAL STUDY

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Abstract
This study presents an empirical assessment of the historical trend, stability, and relative performance of potato (Solanum tuberosum L.) cultivation in Odisha for a 54-year continuous period from 1970 to 2023 in comparison to that of India. The production characteristics of the state were examined against corresponding national benchmarks during the post-Green Revolution period. Secondary time-series data sourced from the Directorate of Economics and Statistics and the Five Decades of Odisha Agricultural Statistics was utilized. The research employs descriptive statistics and test of significance for area, yield and production of potato in Odisha compared to that of India. To verify differences in performances of different variables, a series of parametric tests were executed. The coefficient of variation for production was found to be the highest followed by area and yield. All the three variables showed increasing trend. The results indicate that yield of potato in Odisha is significantly less than that of India whereas the proportion of area and production of potato in Odisha is not significantly different from that of India.

Keywords*:* Descriptive Statistics, Potato, Production, Student's t-test, Test of Significance.

Introduction

In the present agricultural scenario of developing countries, diversified horticultural frameworks are recognized as vital for nutritional security and sustainability of rural livelihood. Among non-cereal crops, potato (Solanum tuberosum L.) stands out as a highly efficient producer of calories and dry matter per unit area, offering high commercial returns for smallholders (Birthal *et al.,* 2022). In India, regional policies have encouraged a structural shift from monoculture rice systems toward high-value vegetable crops during the post-Green Revolution era to elevate farm incomes and increase resource efficiency.

Odisha, situated on the eastern coastal seaboard of India, features distinct agro-climatic zones well-suited for potato production during Rabi cycle. Nonetheless, the state has historically faced difficulties in attaining self-sufficiency regarding potato production, leaving it vulnerable to supply disruptions and price volatility, and turning it into an importer from nearby states like

West Bengal (Naik, 2020). Corrective policy planning requires a solid empirical foundation built on exact statistical parameters rather than aggregate observation alone.

While standard econometric studies focus mainly on complex predictive modeling, a clean analytical look at foundational data properties is required. This paper uses a structured approach focusing on two clear statistical tools: descriptive statistical profiling and tests of significance. This combination evaluates the central tendency, distribution dispersion, and structural variations in Odisha's potato sector. Evaluating the long-term trajectory of area, yield, and production of potato in Odisha relative to the national average from 1970 to 2023 provides information on regional imbalances. By utilizing tests of significance for means, variances, coefficient of variation and proportions, the study checks if the historical gap between Odisha's production profile and national averages reflects deep structural shortfalls or simple random fluctuations (Lal *et al.,* 2023). To interpret the underlying structural variations, erratic shifts, and growth patterns between national trends and the state, the application of both descriptive statistics and tests of significance is essential.

Materials and Methods

The study utilizes a 54-year time series secondary data from 1970 to 2023. The data covers three primary crop parameters: area (thousand hectares), yield (kg/ha), and production (thousand metric tons). The data was sourced from official agricultural statistical publications, including the Directorate of Agriculture and Food Production, Government of Odisha, and the Five Decades of Odisha Agricultural Statistics.

Descriptive statistics:

Mean, $\bar{x} = \frac{\sum_{i=1}^{n} x_i}{n}$

Standard deviation, $\sigma_X = \sqrt{\frac{\sum_{i=1}^{n}(x_i - \bar{x})^2}{n-1}}$

Coefficient of Variation, $CV_X = \frac{\sigma_X}{\bar{x}} \times 100$

Skewness, $\beta_1 = \frac{\mu_3^2}{\mu_2^3}$

Kurtosis, $\beta_2 = \frac{\mu_4}{\mu_2^2}$ **(Mishra *et al.,* 2019)**

Test of significance of yield of potato in Odisha

(a) Mean

Hypotheses are stated as below:

$$H_0: \mu = \mu_0$$

$$H_1: \mu < \mu_0$$

(It is left tailed test since the numerical value of yield of potato in Odisha is less than that of India)

α= Level of significance

Test statistic,

$$t = \frac{\bar{x} - \mu_0}{SE(\bar{x})}$$

$$SE(\bar{x}) = \sqrt{\frac{s^2}{n}}$$

Where,

μ : population mean (i.e. Mean yield of potato in Odisha from 1970 – 2023)

μ_0 : assumed/ expected mean (i.e. Mean yield of potato in India from 1970 – 2023)

$\bar{x}$ gives an estimate of μ

Sample variance, $s^2 = \frac{1}{n-1}\sum_{i=1}^{n}(x_i - \bar{x})^2$

If p value $<$ α, then the test is significant

(b) Variance

χ^2 test for single variance is not used since the yield of potato for India and Odisha are not independent datasets. Therefore F-test is used.

Hypotheses are stated as below:

$$H_0: \frac{\sigma_X^2}{\sigma_Y^2} = 1$$

$$H_1: \frac{\sigma_X^2}{\sigma_Y^2} > 1$$

(The test is right tailed since the variance of yield of potato in India is higher than that of Odisha)

α= Level of significance

$$\text{Test statistic, } F = \frac{s_X^2}{s_Y^2}$$

Where,

σ_X^2: Variance of yield of potato for India from 1970 – 2023

σ_Y^2: Variance of yield of potato for India from 1970 – 2023

Degrees of freedom:

$df_X = n_x - 1$

$df_Y = n_Y - 1$

If p value $<$ α, then the test is significant

(c) Coefficient of Variation (CV)

The hypotheses are stated as below:

$$H_0: CV_1 = CV_2$$

$$H_1: CV_1 \neq CV_2$$

α= Level of significance

Test statistic,

$$Z = \frac{CV_1 - CV_2}{\sqrt{\sigma_1^2 + \sigma_2^2}}$$

$$\sigma_1^2 = \frac{CV_1^2}{2n_1}(1 + CV_1^2) \text{ and } \sigma_2^2 = \frac{CV_2^2}{2n_2}(1 + CV_2^2)$$

Where

CV_1= coefficient of variation of yield of potato in Odisha from 1970 – 2023

CV_2= coefficient of variation of yield of potato in India from 1970 – 2023

σ_1^2= estimated variance of the coefficient of variation of yield of potato in Odisha

σ_2^2= estimated variance of the coefficient of variation of yield of potato in India

n_1= number of years in the time-series dataset of Odisha

n_2= number of years in the time-series dataset of India

Test of proportion for area and production of potato in Odisha

The hypotheses are stated as below:

$$H_0: p = p_0$$

$$H_1: p < p_0$$

(Test is left tailed because proportion in Odisha is less than proportion for area/ production of potato in Odisha is less than that of India)

α =Level of significance

$$Test\ statistic, Z = \frac{\hat{p} - p_0}{SE(\hat{p} - p_0)}$$

$$SE(\hat{p} - p_0) = \sqrt{\frac{p_0(1 - p_0)}{n}}$$

Where,

p: proportion of area or production of potato to that of total vegetables in Odisha from 1970 – 2023

p_0: assumed/ expected proportion of area or production of potato to that of total vegetables in India from 1970 – 2023

$\hat{p}$: sample/ estimated value of p

n: sample size

If p value $< \alpha$, then the test is significant

Results and Discussion

The descriptive statistics of area, yield and production of potato are presented in Table 1. The coefficient of variation is highest for production followed by area and yield. This indicates that yield has highest temporal stability, while area and production show greater annual fluctuations.

This indicates that the yield of potato is more stable over the years. All the three variables show positive skewness. The distribution of all the three variables is platykurtic indicating moderate variability with fewer extreme outliers.

Table 1: Descriptive statistics of area, yield and production of potato in Odisha

Variable	Area ('000ha)	Yield (kg/ha)	Production('000MT)
Mean	12.46	10315.69	135.79
SD	7.31	2510.88	97.45
Median	9.35	10117	91.67
Min	5.34	5169	35.87
Max	35.76	17005	427.94
Range	30.42	11836	392.07
Skewness	1.57	0.48	1.22
Kurtosis	1.49	0.27	0.43
CV (%)	58.69	24.34	71.76

Test of significance of mean for yield of potato:

$\mu_0 = 17265$ kg/ha

$H_0: \mu = 17265$ kg/ha

$H_1: \mu < 17265$ kg/ha (It is left tailed test since the numerical value of yield of potato in Odisha is expected to be less than that of India)

$\alpha = 0.05$

$\bar{x}$ =10315.69 kg/ha

$\bar{x}$ is the sample mean yield which serves as the estimated value for the population mean μ

$SE(\bar{x}) = 2510.88$

$t = \frac{\bar{x} - \mu_0}{SE(\bar{x})} = \mathbf{2.767}$

p value = **0.007**

Since p value < 0.05, null hypothesis is rejected i.e. the mean yield of potato in Odisha is significantly less than that in India during the post green revolution period.

Test of significance of standard deviation for yield of potato:

σ_X = 4739.937

σ_Y =2510.88

$\alpha = 0.01$

$F = \frac{s_X^2}{s_Y^2} = \mathbf{3.563}$

p value = **0.0001**

Since p value < 0.01, null hypothesis is rejected i.e. the standard deviation of yield of potato in Odisha is significantly less than that in India during post green revolution period.

Test of significance of coefficient of variation for yield of potato:

$CV_1 = 24.34$

$CV_2 = 31.18$

$\alpha = 0.05$

$\sigma_1^2 = \frac{CV_1^2}{2n_1}(1 + CV_1^2) = 3255.3$

$\sigma_2^2 = \frac{CV_2^2}{2n_2}(1 + CV_2^2) = 8760.46$

$Z = \frac{CV_1 - CV_2}{\sqrt{\sigma_1^2 + \sigma_2^2}} = \frac{5505.16}{109.61} = \mathbf{50.22}$

p value = **0**

Since p value < 0.05, null hypothesis is rejected i.e. the coefficient of variation of yield of potato in Odisha is significantly less than that in India during post green revolution period.

Test of proportion for area and production of potato:

$p_0 = 0.06$

$H_0: p = 0.06$

$H_1: p < 0.06$

$\hat{p} = 0.009$

$\alpha = 0.05$

$SE(\hat{p} - p_0) = \sqrt{\frac{p_0(1-p_0)}{n}} = 0.03$

$Z = \frac{\hat{p} - p_0}{SE(\hat{p} - p_0)} = \mathbf{1.557}$

p value = **0.063**

Since p value > 0.05, null hypothesis is accepted i.e. the proportion of area and production of potato in Odisha is not significantly different than that in India during post green revolution period.

Conclusion

This study combines descriptive statistics and parametric testing to understand the potato cultivation in Odisha. The descriptive statistics denote stable yield distributions along with highly variable total production patterns. The parametric tests confirm a statistically significant difference in mean, variance, and coefficient of variation of yield of potato in Odisha compared to that of India. These results suggest that policy interventions should move away from broad land expansion and focus on narrowing the yield gap by improving access to high-yielding seed varieties, expanding cold storage options, and implementing reliable irrigation infrastructure.

References

1. Birthal, P. S., Sharma, G., & Kumar, S. (2022). High-value horticulture and agricultural diversification in India: Trends, drivers, and policy options. *Food Policy, 108*, 102241.
2. Lal, P., Tiwari, R. K., Behera, B., Yadav, M. R., Sharma, E., Altaf, M. A., ... & Kumar, R. (2023). Exploring potato seed research: A bibliometric approach towards sustainable food security. *Frontiers in Sustainable Food Systems, 7*, 1229272.
3. Mishra, P., Pandey, C. M., Singh, U., Gupta, A., Sahu, C., & Keshri, A. (2019). Descriptive statistics and normality tests for statistical data. *Annals of Cardiac Anaesthesia, 22*(1), 67–72.
4. Naik, A. K. (2020). Supply chain dynamics and price transmission efficiency in vegetable markets: A case study of Odisha's potato economy. *Indian Journal of Agricultural Economics, 75*(3), 342–356.

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ARTIFICIAL INTELLIGENCE AND REMOTE SENSING FOR CLIMATE RESILIENCE AND PRECISION AGRICULTURE

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Abstract

The convergence of artificial intelligence (AI) and remote sensing technologies is fundamentally transforming how humanity monitors, manages, and adapts its agricultural systems in the face of accelerating climate change. This chapter provides a comprehensive examination of the technical foundations, operational frameworks, and real-world deployments of AI-driven remote sensing across two interlinked domains: climate resilience and precision agriculture. Drawing on satellite constellations, unmanned aerial vehicles (UAVs), ground-based sensor networks, and a spectrum of machine learning architectures, we explore how these tools enable near-real-time monitoring of crop health, soil conditions, water resources, and extreme weather events at scales ranging from individual farm fields to entire continents. Emerging frontiers — from federated learning for farm-level privacy to digital twins for climate scenario modelling — are examined as signposts toward a more data-driven, equitable, and climate-resilient global agriculture.

1. Introduction

Global food demand is projected to increase by 50 to 70 per cent by 2050, driven by population growth, urbanisation, and shifting dietary preferences.[1] Simultaneously, climate change is reshaping the very conditions under which food is produced: growing seasons are shifting, precipitation patterns are becoming more erratic, extreme heat events are intensifying, and the incidence of novel plant diseases is rising.[2] The window within which humanity must resolve this paradox is narrowing.

Remote sensing and artificial intelligence, individually powerful, become transformative when fused together. Satellite platforms, drones, and ground-based sensors generate petabytes of spatially explicit data about the Earth's surface every day.[3] It is AI — in particular, the family of techniques encompassed by machine learning and deep learning — that converts raw spectral, thermal, and radar signals into knowledge: where a crop is stressed, when to irrigate, which fields are at risk of flooding, how a heatwave is reshaping regional food supply chains.[4]

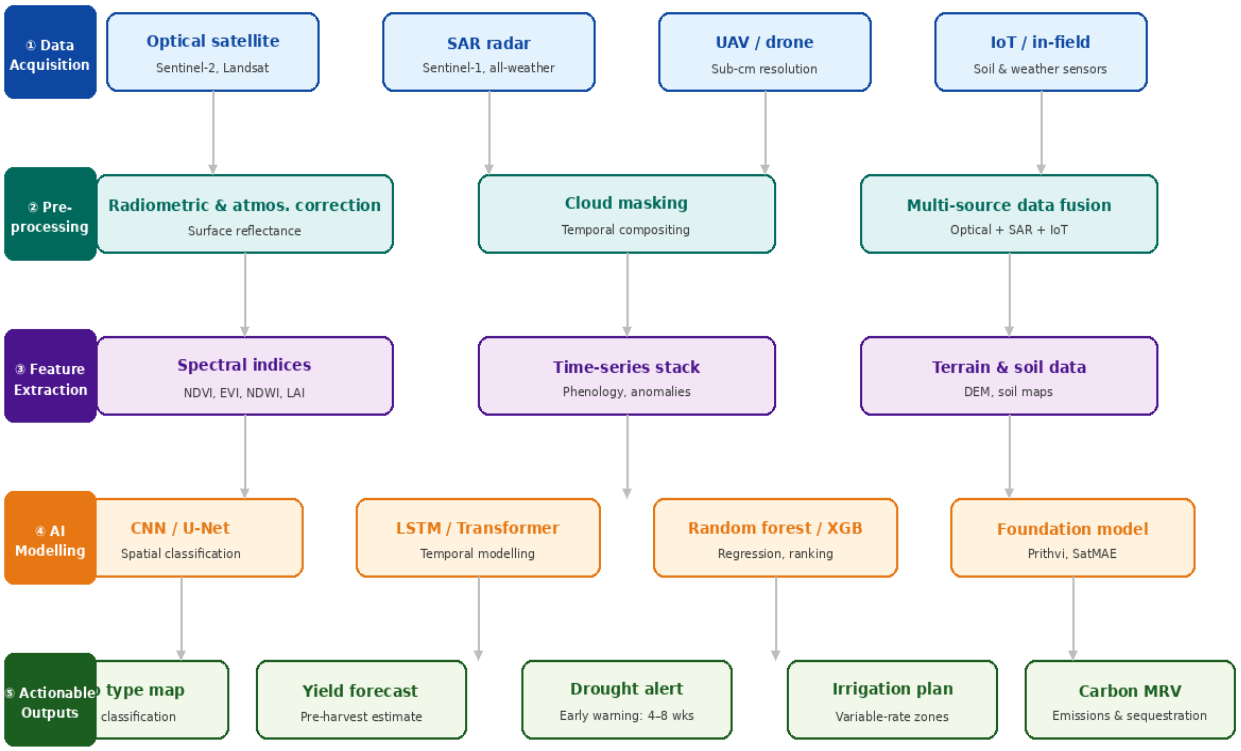

Figure 1: The AI-Remote Sensing Pipeline — from raw satellite and sensor data through preprocessing, feature extraction, and AI modelling to actionable farm management outputs

This chapter is organised to build understanding progressively. We begin with the scientific foundations of remote sensing as applied to vegetation and climate systems, then introduce the principal AI methodologies, and finally examine precision agriculture and climate resilience as distinct but deeply interrelated application arenas.

2. Scientific Foundations

2.1 The Electromagnetic Spectrum and Vegetation

Remote sensing derives its power from the differential interaction of electromagnetic radiation with physical surfaces.[23] Healthy green vegetation exhibits a highly characteristic spectral signature: strong absorption in the blue (450–490 nm) and red (620–700 nm) regions due to chlorophyll pigments, very high reflectance in the near-infrared (700–1300 nm) resulting from internal leaf cell structure, and variable reflectance in the shortwave infrared (1300–2500 nm) sensitive to leaf water content.[24]

The Normalised Difference Vegetation Index (NDVI), calculated as (NIR − Red) / (NIR + Red), remains one of the most widely used proxies for green biomass and photosynthetic activity.[13] More sophisticated indices have been developed for specific diagnostic purposes: the Enhanced Vegetation Index (EVI) reduces atmospheric and soil background noise; the Leaf Area Index (LAI) quantifies canopy density; and the Red-Edge Chlorophyll Index is particularly sensitive to early-stage nutrient stress.[14]

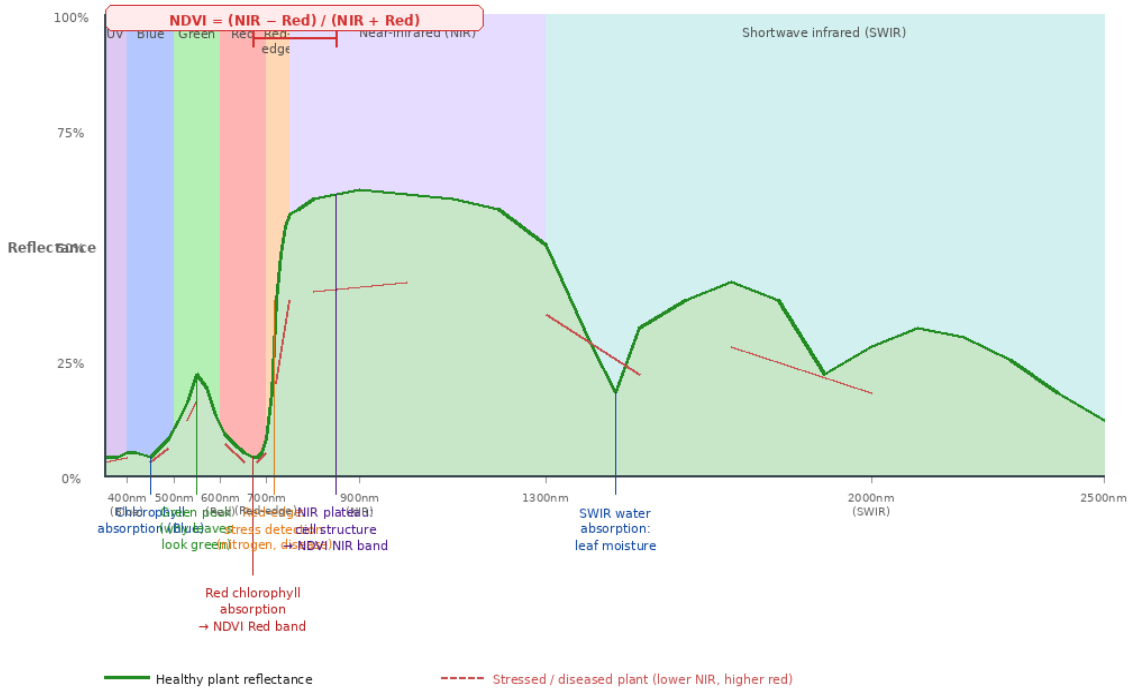

Figure 2: The vegetation spectral reflectance curve — showing the physical basis of remote sensing vegetation indices. The red-edge region (700–750 nm) is especially sensitive to early plant stress before visible symptoms appear

The diagram above illustrates why vegetation indices work: the dramatic contrast between low red reflectance and high NIR reflectance in healthy plants creates a strong, measurable signal that degrades predictably under drought, disease, or nutrient deficiency.[13,14] This enables AI models to detect crop stress weeks before it becomes visible to the human eye.[5]

Table 1: Key Remote Sensing Technologies and Agricultural Applications

Technology	Primary Application	Key Benefit
Multispectral (Sentinel-2, Landsat)	Crop stress & health mapping	Early detection of disease, drought, nutrient deficiency
SAR (Synthetic Aperture Radar)	Soil moisture & flood mapping	Cloud-penetrating, all-weather monitoring
LiDAR	Terrain & canopy structure	High-precision 3D vegetation mapping
Hyperspectral sensors	Species & mineral identification	Narrow-band spectral signatures for fine discrimination
Thermal infrared	Water stress & ET estimation	Canopy temperature as irrigation proxy

2.2 Remote Sensing Platforms

The Sentinel-1 SAR constellation is particularly valuable because it penetrates cloud cover — a critical advantage in tropical and monsoon-dominated agricultural regions where optical sensors are frequently obscured.[18] Unmanned aerial vehicles equipped with multispectral, hyperspectral,

thermal, or LiDAR sensors can generate imagery at sub-centimetre resolutions, enabling detection of individual diseased plants and precise canopy height measurements.[23] Google Earth Engine has dramatically reduced the computational barriers to deploying large-scale remote sensing pipelines by providing petabyte-scale data archives co-located with scalable compute infrastructure.[3]

3. Artificial Intelligence Methodologies

3.1 Machine Learning Overview

Traditional machine learning methods — decision trees, random forests, support vector machines, and gradient-boosting algorithms such as XGBoost — perform well when training data is limited and interpretability is required.[8] The introduction of deep learning, particularly convolutional neural networks (CNNs), has dramatically expanded the range of tasks addressable by remote sensing AI.[21] For tasks such as land cover classification, crop type mapping, and object detection, deep learning models consistently outperform traditional approaches when sufficient labelled training data is available.[4,15]

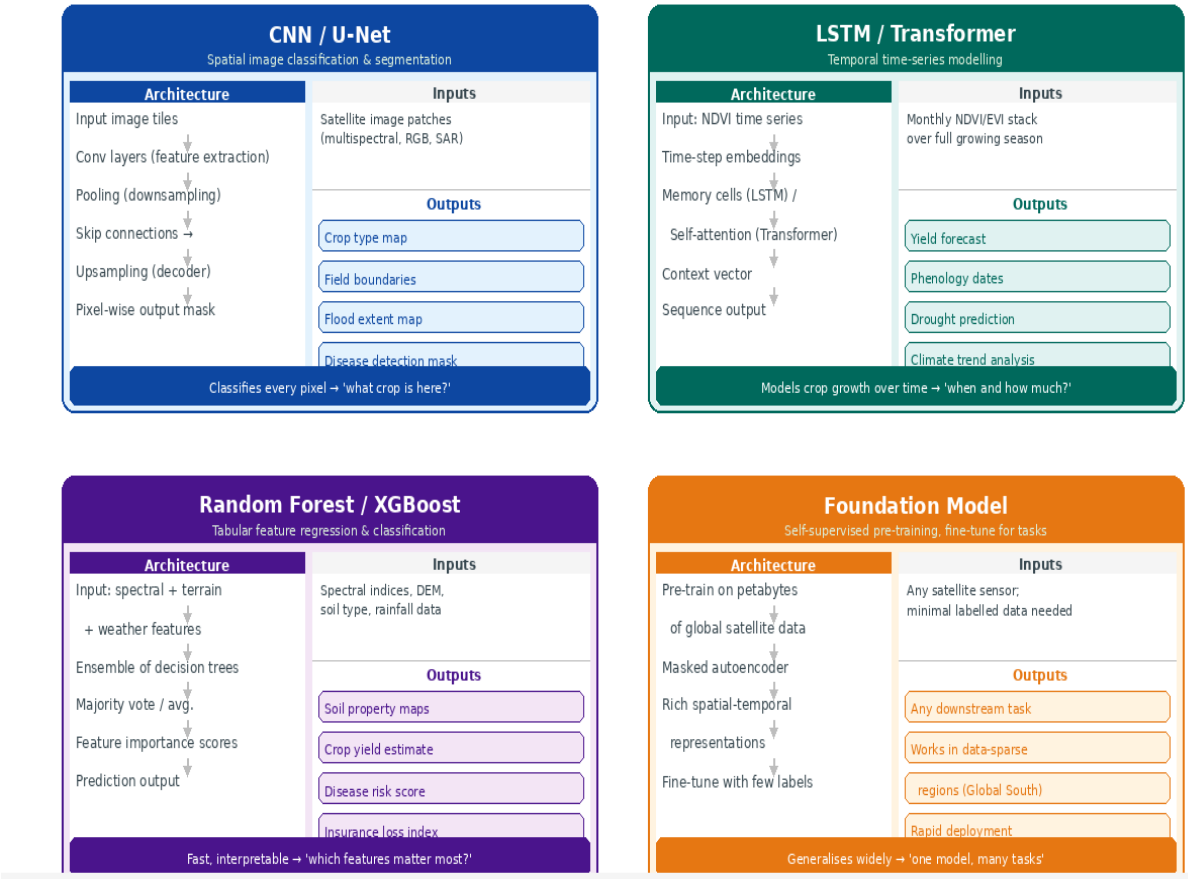

Figure 3: Four main AI model families in agricultural remote sensing — CNN/U-Net for spatial classification, LSTM/Transformer for temporal dynamics, Random Forest/XGBoost for interpretable regression, and Foundation Models for generalisation across data-sparse regions

For pixel-level segmentation tasks — delineating field boundaries, mapping flooded areas — encoder-decoder architectures, most prominently U-Net, have become the dominant paradigm.[15] Long Short-Term Memory networks and the Transformer architecture have been applied to time-series of satellite-derived spectral indices to model crop phenology, detect anomalous growing conditions, and forecast end-of-season yields.[6] Foundation models pre-trained on petabyte-scale satellite archives, such as Prithvi (IBM and NASA) and SatMAE, enable rapid fine-tuning to new regions and tasks with minimal labelled data.[7]

Table 2: AI Methods and Their Remote Sensing Applications

AI Method	Remote Sensing Input	Agricultural / Climate Use Case
Convolutional Neural Networks	Satellite & UAV imagery	Crop type classification, disease detection
Random Forest / XGBoost	Multispectral indices (NDVI…)	Yield prediction, soil property mapping
LSTM / Transformer	Time-series satellite data	Phenology modelling, climate trend analysis
U-Net Segmentation	High-resolution imagery	Field boundary delineation, flood mapping
Transfer Learning	Multi-source imagery	Domain adaptation with limited labelled data
Foundation Models (Prithvi, SatMAE)	Any multi-sensor archive	Multi-task learning in data-sparse regions

3.2 Data Fusion

Modern AI systems routinely fuse data from multiple sources: optical and SAR imagery provide complementary information; satellite-derived products are fused with in-situ sensor readings; and spatial remote sensing data is combined with tabular meteorological records, soil databases, and agronomic knowledge.[14,18] Attention-based fusion architectures dynamically weight the contribution of each modality based on its relevance for a given spatial location and time step.[6]

4. Precision Agriculture

Precision agriculture refers to the suite of practices that use spatially and temporally variable information about field conditions to tailor management decisions to specific zones within a field.[12] Variable-rate fertilisation trials consistently demonstrate reductions of 10–25% in input costs; precision irrigation systems reduce water use by 30–50% relative to conventional scheduling in many cropping systems.[13,29]

4.1 Crop Health Monitoring and Disease Detection

Plant diseases and pest infestations impose an estimated 20–40% loss on global crop production annually.[5] Deep learning applied to UAV-acquired RGB imagery has demonstrated accuracies exceeding 90% for detecting wheat streak mosaic virus, late blight in potato, and grey leaf spot in maize in controlled trials.[5] The CIMMYT mobile phone-based disease identification system,

deployed across South Asia, combines CNN image classification with GPS geo-tagging to generate near-real-time disease spread maps, reducing fungicide use by 18% in field trials.[19]

4.2 Yield Prediction

Machine learning approaches that incorporate multi-dimensional input spaces — combining spectral time series with weather reanalyses, soil maps, and agronomic calendar information — substantially outperform simple regression models, particularly in years with anomalous weather.[9] AI systems integrating Sentinel-2 time series with ERA5 climate reanalysis have achieved mean absolute percentage errors below 8% for major cereals at district level in multiple countries.[8,9]

4.3 Precision Irrigation

Remote sensing-based evapotranspiration estimation, using thermal infrared imagery and energy balance models such as SEBAL and METRIC, enables spatially distributed irrigation scheduling at field scale.[13] Operational irrigation scheduling systems deployed in California, Spain, and India's command area systems have reduced water use by 20–40% relative to calendar-based scheduling without yield penalty.[12,13]

5. Climate Resilience: Monitoring, Adaptation, and Early Warning

Climate resilience in agriculture encompasses the capacity to anticipate, absorb, accommodate, and recover from climate-related stresses.[2] Remote sensing and AI are central to all four dimensions of this resilience cycle.[7]

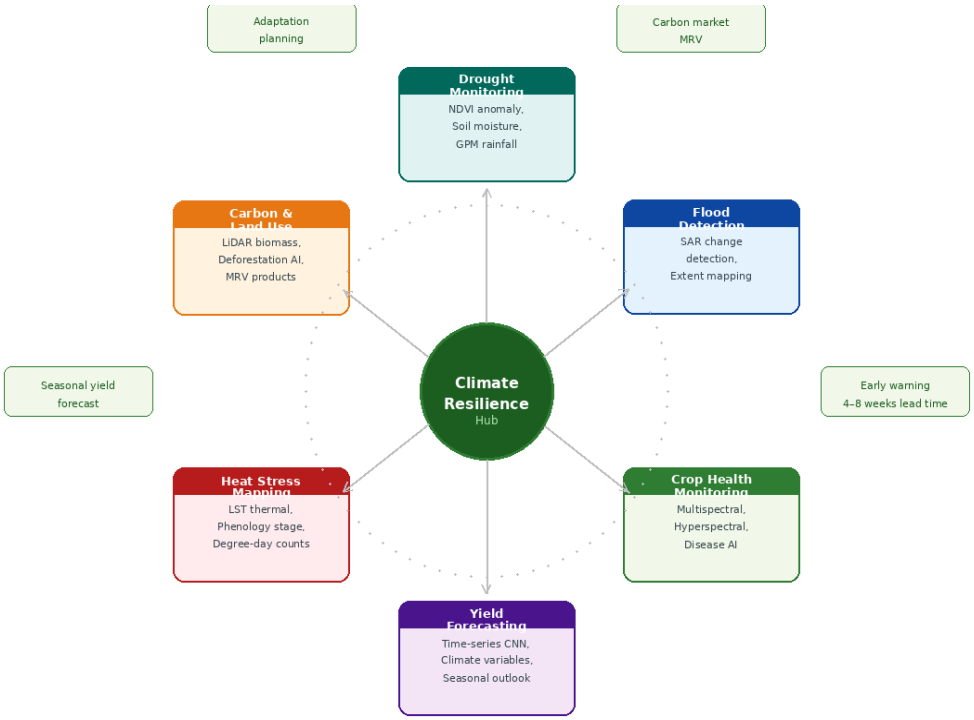

Figure 4: The AI-enabled climate resilience cycle for agriculture. Six remote sensing monitoring domains feed actionable outcomes, integrated through a central Climate Resilience Hub

5.1 Drought Monitoring and Early Warning

The integration of multiple remote sensing drought indicators — NDVI anomalies, SAR-derived soil moisture, land surface temperature anomalies, and satellite precipitation estimates — into composite drought indices using machine learning ensemble methods substantially outperforms any single indicator.[7,18] Deep learning models trained on historical drought event archives can forecast vegetation stress responses 4–8 weeks in advance, sufficient lead time to activate drought preparedness measures.[7]

Case Study: AI-Enabled Drought Early Warning in the Sahel

The FEWS NET system fuses MODIS vegetation anomaly data, CHIRPS rainfall estimates, and population vulnerability indicators using machine learning to produce agricultural drought severity maps at 10-day intervals. During the 2021–2022 East Africa drought, early warning alerts were issued more than three months before peak food insecurity was observed, allowing humanitarian agencies to pre-position assistance. Retrospective analysis estimated prevention of 1.4 million people falling into crisis-level food insecurity.

5.2 Flood Detection

SAR sensors operating in C-band and L-band wavelengths are the instrument of choice for flood detection because they penetrate cloud cover and distinguish open water from surrounding land through differences in radar backscatter.[18] Deep learning-based change detection networks applied to pre-flood and flood-peak Sentinel-1 acquisitions have achieved flood extent mapping accuracies above 95% in multiple benchmark datasets.[15]

5.3 Carbon Sequestration and Land Use Change

AI-powered deforestation alert systems — most prominently the PRODES and DETER products of Brazil's National Institute for Space Research — use change detection algorithms applied to daily MODIS and Sentinel-2 imagery to detect clearings in near-real time.[22] Machine learning models that integrate soil spectroscopy, terrain derivatives, and management practice data are emerging as the basis for low-cost, spatially explicit soil carbon stock estimation at national scales.[7,13]

6. Regional Perspectives

The benefits of AI-driven agricultural remote sensing vary profoundly across regions.[1] The agro-climatic context, farming system structure, infrastructure endowment, institutional capacity, and data governance environment differ enough across the Sahel, the Indo-Gangetic Plain, Southeast Asian deltas, Latin American soy frontiers, and European peri-urban horticulture that regional analysis is indispensable.[28]

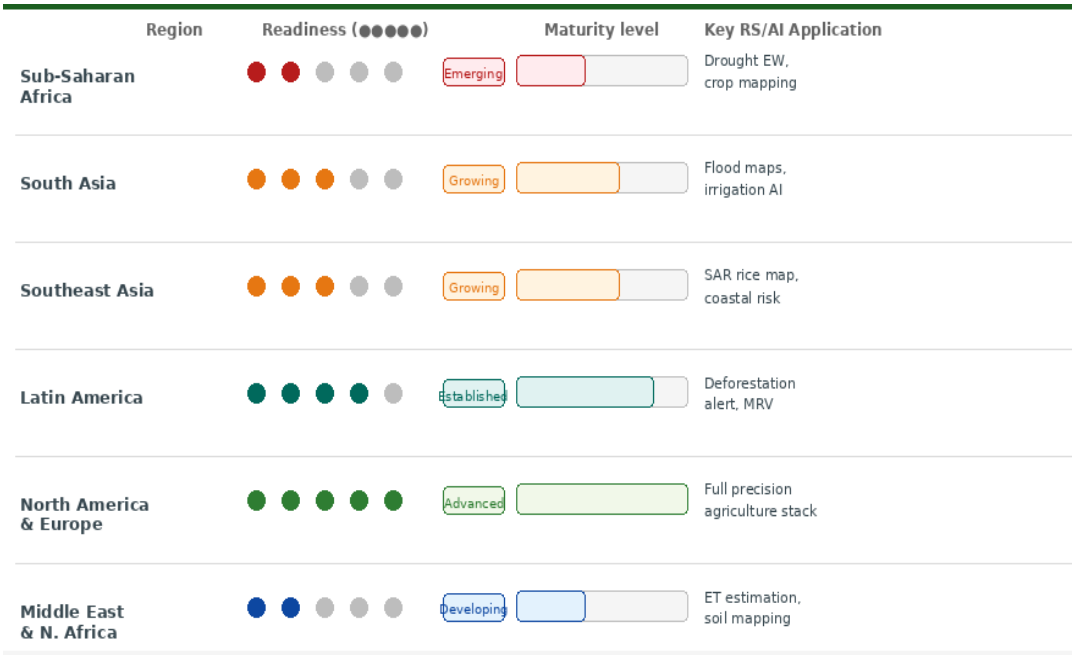

Figure 5: Regional AI-remote sensing readiness for agriculture. Scores reflect infrastructure availability, open data access, institutional capacity, and scale of operational deployment

Table 3: Regional AI and Remote Sensing Landscape in Agriculture

Region	Primary Challenge	Key RS/AI Application	Notable Initiative	Readiness
Sub-Saharan Africa	Food insecurity, erratic rainfall	Drought early warning, crop mapping	FEWS NET, PlantVillage	Emerging
South Asia	Monsoon variability, flood risk	Flood mapping, irrigation AI	CIMMYT, ICAR	Growing
Southeast Asia	Deforestation, rice monitoring	SAR rice mapping, coastal risk	SERVIR-Mekong, IRRI	Growing
Latin America	Amazon conversion, drought	Deforestation alert, MRV	MapBiomas, INPE	Established
N. America & Europe	Input optimisation, carbon MRV	Full precision agriculture stack	John Deere Ops Centre	Advanced
Middle East & N. Africa	Water scarcity, salinisation	ET estimation, soil mapping	ICARDA, FAO WaPOR	Developing

6.1 Sub-Saharan Africa

The development of sub-10-metre resolution commercial satellite constellations — combined with transfer learning techniques adapting models trained on data-rich regions to data-sparse African contexts — has substantially improved crop type mapping accuracy.[19] The PlantVillage network has deployed AI-based crop disease diagnosis to over 30 million farmers across Africa through a mobile application requiring no internet connectivity for inference.[5]

6.2 South Asia

India's Pradhan Mantri Fasal Bima Yojana (PMFBY) crop insurance scheme, covering over 50 million smallholder farmers, has integrated satellite-based remote sensing into its crop loss assessment framework.[9] AI-based yield loss estimation models trained on historical claim data and satellite observations have reduced settlement times from months to weeks while improving fairness and fraud detection.[9]

6.3 Latin America

The MapBiomas initiative has produced annual land use and land cover maps of Brazil's entire territory at 30 m resolution from 1985 to the present, enabling tracking of every conversion from forest to pasture to cropland.[22] This extraordinary four-decade archive underpins supply chain sustainability certification, government land use planning, and UNFCCC reporting.[22]

7. Ethics, Governance, and Policy Frameworks

The integration of artificial intelligence into agricultural management raises ethical questions of genuine importance.[25] Algorithmic accountability, data sovereignty, climate justice, and digital equity must be addressed as core design requirements.[28] Open satellite data as public infrastructure — exemplified by the landmark 2008 decision to make the entire Landsat archive freely available — has been the single most consequential policy enabling the agricultural remote sensing ecosystem.[3]

The rapidly growing volume of farm-generated data creates urgent governance questions about ownership, privacy, portability, and competition.[25,26] The European Union's Data Act (2023) and Farm to Fork Strategy's provisions create new rights for agricultural data generators — including farmers — to access their own data, port it between service providers, and share it with third parties of their choosing.[28]

8. Emerging Frontiers

A new generation of orbital hyperspectral sensors — including ESA's Copernicus Hyperspectral Imaging Mission (CHIME) and NASA's EMIT spectrometer — will bring hyperspectral imaging capabilities previously available only to airborne platforms to orbit at global scale.[27] Federated learning offers a path to training powerful AI models on the collective intelligence of many farms without centralising sensitive data.[21] Digital twins of agricultural watersheds, combining process-based crop models with continuous remote sensing data assimilation, will enable

prospective climate scenario analysis at farm scale.[7] Geospatial foundation models pre-trained on petabyte archives are beginning to deliver the 'train once, deploy everywhere' capability needed to make precision agriculture accessible to data-sparse smallholder contexts.[7,19]

Conclusions

The integration of artificial intelligence with remote sensing technologies represents one of the most consequential developments in the history of agricultural science.[12] AI-driven systems can detect plant diseases before visible symptoms appear, predict seasonal yields months in advance, track drought onset across entire river basins, map flood damage within hours, and quantify soil carbon stocks at national scales.[5,9,18]

The five diagrams in this chapter together tell a single coherent story: light is reflected from vegetation with a spectral signature encoding plant health (Figure 7.2); that signal travels through a carefully engineered AI pipeline (Figure 7.1) powered by four model families (Figure 7.3); the outputs drive six interconnected climate resilience monitoring systems (Figure 7.4); and the capacity to realise these benefits varies across the globe in ways that demand equity-centred policy (Figure 5).

Realising this potential requires simultaneous advances across technical, institutional, and policy dimensions.[1,2] The pixels are available. The algorithms exist. What remains is the human and institutional commitment to ensure the resulting intelligence flows to all farmers, in all regions, facing all aspects of a changing climate.[28]

References

1. Food and Agriculture Organization of the United Nations. (2021). *The state of food and agriculture: Making agrifood systems more resilient to shocks and stresses*. FAO.
2. Intergovernmental Panel on Climate Change. (2022). *Climate change 2022: Impacts, adaptation and vulnerability. Contribution of Working Group II to the Sixth Assessment Report*. Cambridge University Press.
3. Gorelick, N., Hancher, M., Dixon, M., Ilyushchenko, S., Thau, D., & Moore, R. (2017). Google Earth Engine: Planetary-scale geospatial analysis for everyone. *Remote Sensing of Environment, 202*, 18–27.
4. Zhu, X. X., Tuia, D., Mou, L., Xia, G. S., Zhang, L., Xu, F., et al. (2017). Deep learning in remote sensing: A comprehensive review and list of resources. *IEEE Geoscience and Remote Sensing Magazine, 5*(4), 8–36.
5. Mohanty, S. P., Hughes, D. P., & Salathé, M. (2016). Using deep learning for image-based plant disease detection. *Frontiers in Plant Science, 7*, 1419.
6. Rußwurm, M., & Körner, M. (2020). Self-attention for raw optical satellite time series classification. *ISPRS Journal of Photogrammetry and Remote Sensing, 169*, 421–435.

7. Reichstein, M., Camps-Valls, G., Stevens, B., Jung, M., Denzler, J., Carvalhais, N., et al. (2019). Deep learning and process understanding for data-driven Earth system science. *Nature, 566*, 195–204.
8. Chlingaryan, A., Sukkarieh, S., & Whelan, B. (2018). Machine learning approaches for crop yield prediction and nitrogen status estimation in precision agriculture: A review. *Computers and Electronics in Agriculture, 151*, 61–69.
9. van Klompenburg, T., Kassahun, A., & Catal, C. (2020). Crop yield prediction using machine learning: A systematic literature review. *Computers and Electronics in Agriculture, 177*, 105709.
10. Lobell, D. B., Schlenker, W., & Costa-Roberts, J. (2011). Climate trends and global crop production since 1980. *Science, 333*(6042), 616–620.
11. Wheeler, T., & von Braun, J. (2013). Climate change impacts on global food security. *Science, 341*(6145), 508–513.
12. Gebbers, R., & Adamchuk, V. I. (2010). Precision agriculture and food security. *Science, 327*(5967), 828–831.
13. 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.
14. Ball, J. E., Anderson, D. T., & Chan, C. S. (2017). Comprehensive survey of deep learning in remote sensing: Theories, tools and challenges for the community. *Journal of Applied Remote Sensing, 11*(4), 042609.
15. Ma, L., Liu, Y., Zhang, X., Ye, Y., Yin, G., & Johnson, B. A. (2019). Deep learning in remote sensing applications: A meta-analysis and review. *ISPRS Journal of Photogrammetry and Remote Sensing, 152*, 166–177.
16. Challinor, A. J., Watson, J., Lobell, D. B., Howden, S. M., Smith, D. R., & Chhetri, N. (2014). A meta-analysis of crop yield under climate change and adaptation. *Nature Climate Change, 4*, 287–291.
17. Lobell, D. B., & Asseng, S. (2017). Comparing estimates of climate change impacts from process-based and statistical crop models. *Nature Climate Change, 7*, 811–816.
18. Bauer-Marschallinger, B., Freeman, V., Cao, S., Paulik, C., Schaufler, S., Stachl, T., et al. (2019). Toward global soil moisture monitoring with Sentinel-1: Harnessing assets and overcoming obstacles. *IEEE Transactions on Geoscience and Remote Sensing, 57*(1), 520–539.
19. Kerner, H., Tseng, G., Becker-Reshef, I., Nakalembe, C., Barker, B., Munshell, B., et al. (2020). Rapid response crop maps in data sparse regions. In *ACM SIGKDD Workshop on Humanitarian Mapping*.

20. Tuia, D., Flamary, R., & Courty, N. (2016). Multiclass feature learning for hyperspectral image classification: Sparse and hierarchical solutions. *ISPRS Journal of Photogrammetry and Remote Sensing, 117*, 156–168.
21. LeCun, Y., Bengio, Y., & Hinton, G. (2015). Deep learning. *Nature, 521*, 436–444.
22. Samasse, K., Hanan, N. P., Tappan, G., & Diallo, M. Y. (2018). Assessing cropland area in West Africa for agricultural yield analysis. *Remote Sensing, 10*(11), 1785.
23. Campbell, J. B., & Wynne, R. H. (2011). *Introduction to remote sensing* (5th ed.). Guilford Press.
24. Jensen, J. R. (2015). *Introductory digital image processing: A remote sensing perspective* (4th ed.). Pearson.
25. Carolan, M. (2020). Automated agrifood futures: Robotics, labor and the distributive politics of digital agriculture. *Journal of Peasant Studies, 47*(1), 184–207.
26. Aubert, B. A., Schroeder, A., & Grimaudo, J. (2012). IT as enabler of sustainable farming: An empirical analysis of farmers' adoption decision of precision agriculture technology. *Decision Support Systems, 54*(1), 510–520.
27. Zhang, L., Shi, W., & Zhang, B. (2021). A comparison of agglomeration indices: Toward a comprehensive measure of spatial concentration. *Journal of Regional Science, 14*(4), 4958–4972.
28. CGIAR Platform for Big Data in Agriculture. (2021). *Principles for responsible investment in agriculture and food systems*. CGIAR System Organization.
29. Pierpaoli, E., Carli, G., Pignone, E., & Rinaldi, M. (2013). Drivers of precision agriculture technologies adoption: A literature review. *Procedia Technology, 8*, 61–69.
30. Lillesand, T., Kiefer, R. W., & Chipman, J. (2015). *Remote sensing and image interpretation* (7th ed.). John Wiley & Sons.

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AGRICULTURAL MECHANIZATION AND RURAL LABOR TRANSITION IN THE ERA OF SMART FARMING

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Introduction

Agriculture across the world is undergoing rapid transformation due to technological advancement, changing labor markets, and increasing pressure to improve productivity. In India, these changes are especially visible in the growing use of agricultural machinery for farm operations. Mechanization has become an important component of modern farming systems because it helps farmers perform agricultural activities more efficiently and within limited time periods. In recent years, the idea of *smart agriculture* has further strengthened the importance of mechanization by combining modern machinery with improved farm management, scientific planning, and technology-driven decision-making.

The agricultural sector in India continues to face several structural problems such as labor shortages during peak seasons, rising wage rates, migration of rural workers, and shrinking farm profitability. These issues are more serious in regions dominated by small and fragmented holdings, including Assam and many parts of eastern India. Under such conditions, mechanization is increasingly viewed as a practical solution for improving farm efficiency and reducing dependence on manual labor.

However, the influence of mechanization on agricultural labor is not straightforward. Machinery certainly reduces the labor requirement for several operations, but at the same time it may also increase labor demand indirectly by encouraging farmers to cultivate more land or grow multiple crops in a year. Therefore, mechanization does not simply replace labor; rather, it changes the pattern, timing, and nature of labor use in agriculture. This chapter examines how mechanization affects agricultural labor within the broader framework of smart agriculture. It discusses the labour-saving role of machinery, the continued importance of human labor, emerging employment opportunities, and the measures required for inclusive mechanization.

Mechanization as a Component of Smart Agriculture

Smart agriculture refers to the application of modern technologies and scientific methods to improve agricultural productivity, resource efficiency, and sustainability. Mechanization forms

one of the core elements of this transformation because modern agricultural systems rely heavily on machines for timely and efficient farm operations.

The use of tractors, power tillers, threshers, harvesters, seed drills, irrigation pumps, and other farm implements has expanded significantly over the past few decades. These technologies reduce the time required for farm operations and help farmers complete agricultural activities within critical seasonal windows. Timely operations are particularly important in regions where weather conditions are uncertain and cropping seasons are short.

Mechanization also supports other dimensions of smart agriculture. Precision farming, improved irrigation systems, digital farm management, and advanced crop monitoring technologies become more effective when supported by mechanized operations. Thus, agricultural machinery is not only a source of physical power but also an important tool for improving productivity and efficiency in modern farming systems.

Reduction in Labor Requirement through Mechanization

One of the most noticeable effects of mechanization is the decline in labor required for many agricultural operations. Traditional farming methods depend heavily on human and animal labor, especially for land preparation, threshing, irrigation, and transportation. Modern machinery can perform these tasks more quickly and efficiently. Studies comparing traditional and mechanized farms show a clear difference in labor use. Bullock-operated farms generally require much higher labor input than farms using tractors and threshers. In many cases, mechanized farms can complete the same operations with considerably fewer man-days.

The introduction of tractors and threshers has reduced labor use in several ways:

- Less dependence on family labor for cultivation activities.
- Reduced requirement for hired workers during land preparation and threshing.
- Decline in the need for permanent agricultural labourers.
- Faster completion of agricultural operations.
- Higher labor productivity per worker.

For example, a tractor can prepare a field within a few hours, whereas traditional ploughing with bullocks may require several days. Similarly, mechanical threshers process harvested crops much faster than manual methods.

Mechanization is especially valuable in situations where labor shortages occur during peak agricultural seasons. Delays in sowing or harvesting often reduce crop productivity, and machinery helps farmers avoid such losses by ensuring timely farm operations.

Cropping Intensity and the Changing Nature of Labor Demand

Although mechanization reduces labor requirements for specific activities, it does not necessarily reduce total labor demand in agriculture. In many farming systems, mechanization has contributed to increased cropping intensity, which in turn creates additional demand for labor.

Cropping intensity refers to the number of crops grown on the same piece of land during a year. Mechanized land preparation and faster harvesting allow farmers to cultivate multiple crops within shorter intervals. As a result, agricultural activities become more intensive and continuous.

When farmers shift from single cropping to double or triple cropping systems, the overall volume of farm work increases. Certain operations such as transplanting, weeding, fertilizer application, harvesting of delicate crops, sorting, and post-harvest handling still require substantial human labor. Therefore, the demand for labor remains high in many agricultural systems despite the growing use of machinery.

This situation highlights an important feature of mechanization: machinery often changes the distribution and timing of labor rather than eliminating labor completely. Labor demand may decline in one activity while increasing in another. Thus, mechanization and labor can coexist within modern agricultural systems.

Continued Importance of Human Labor

Despite rapid technological progress, agriculture still depends heavily on human labor. Many agricultural operations involve biological variability, changing field conditions, and delicate handling that machines cannot easily manage.

Tasks such as transplanting seedlings, manual weeding, fruit picking, vegetable harvesting, grading, and sorting often require careful judgment and precision. Human workers are able to adapt to uneven land conditions, crop variations, and unexpected environmental changes more effectively than machines.

The limitations of mechanization are more visible in regions with difficult geographical conditions. In Assam, for example, agriculture is characterized by fragmented landholdings, flood-prone areas, and irregular field sizes. Large machinery is often unsuitable under such conditions, making complete mechanization difficult.

As a result, agricultural labor continues to play a central role in crop production. Even highly mechanized farming systems still require human involvement for supervision, management, and several labour-intensive operations.

Mechanization and Rural Employment Opportunities

Mechanization does not only influence labor within the farm sector; it also creates employment opportunities outside traditional cultivation activities. The expansion of agricultural machinery has increased the demand for technical services, repair work, machinery operation, and equipment maintenance.

New forms of rural employment associated with mechanization include:

- Tractor and power tiller operation.
- Repair and servicing of agricultural machinery.

- Manufacturing and assembly of farm equipment.
- Spare parts distribution and sales.
- Machinery rental services.
- Transportation and logistics support.

In many rural areas, young people are increasingly finding employment as machine operators, mechanics, and agricultural service providers. The growth of machinery hiring services has also created opportunities for rural entrepreneurship.

Therefore, mechanization does not simply reduce employment opportunities. Instead, it changes the structure of rural employment by shifting labor from physically demanding manual work toward more technical and service-oriented activities.

Unequal Access to Mechanization

The benefits of mechanization are not equally shared among all categories of farmers. Large farmers generally adopt machinery more easily because they possess greater financial resources and cultivate larger areas of land. Small and marginal farmers, on the other hand, often face serious difficulties in purchasing expensive machinery.

Several factors limit the adoption of mechanization among small farmers:

- High cost of agricultural machinery.
- Limited access to institutional credit.
- Small and fragmented landholdings.
- Inadequate repair and maintenance facilities.
- Lack of technical knowledge and training.

Since small and marginal farmers constitute the majority of agricultural households in India, unequal access to machinery can widen economic disparities within rural areas. Farmers who cannot adopt modern technology may continue to depend heavily on manual labor and experience lower productivity.

This challenge is particularly important within the context of smart agriculture, where access to technology plays a crucial role in determining agricultural competitiveness and income growth.

Mechanization in Assam: Challenges and Prospects

Assam presents a unique situation in the discussion of agricultural mechanization. Agriculture in the state is dominated by small farms, traditional rice cultivation, and difficult agro-climatic conditions. Frequent floods, uneven terrain, and poor rural infrastructure often restrict the use of large farm machinery.

However, smaller and more adaptable technologies such as power tillers, mini-tractors, portable threshers, and small irrigation pumps are becoming increasingly popular. These machines are more suitable for the field conditions found in many parts of the state.

Government support through subsidy schemes, farmer training programs, and agricultural development initiatives has encouraged gradual adoption of mechanization. Nevertheless, the pace of mechanization remains slower compared to agriculturally advanced regions of India.

For Assam, the future of mechanization lies in promoting location-specific and smallholder-friendly technologies that can improve productivity without excluding resourcepoor farmers.

Conclusion

Mechanization has become an integral part of modern agriculture and plays a major role in the transition toward smart farming systems. Its influence on agricultural labor is both direct and indirect. On one hand, machinery reduces labor requirements for operations such as ploughing, threshing, and transportation. On the other hand, it encourages higher cropping intensity and agricultural expansion, which may increase labor demand in several other activities.

The impact of mechanization on labor therefore cannot be understood only in terms of labor displacement. Mechanization changes the nature of agricultural work, improves labor productivity, creates new employment opportunities, and transforms rural economic structures.

At the same time, complete mechanization remains difficult in many regions due to geographical, economic, and technological constraints. Human labor continues to be essential for several agricultural activities that require adaptability and precision.

For states such as Assam, the successful integration of mechanization into smart agriculture depends on the promotion of affordable, location-specific, and smallholder-oriented technologies. Inclusive policy support, particularly through Custom Hiring Centres, financial assistance, and technical training, is necessary to ensure that the benefits of mechanization are shared widely across rural society.

Ultimately, balanced and inclusive mechanization can reduce labor drudgery, improve farm efficiency, strengthen rural livelihoods, and contribute to sustainable agricultural development in the era of smart agriculture.

References

1. Government of India, Ministry of Agriculture and Farmers Welfare. (2024). *Agricultural mechanization in India: Annual report 2023–24*.
2. Indian Council of Agricultural Research (ICAR). (2024). *Technical report on revolutionizing agriculture: The digital transformation of farming*. ICAR, New Delhi.
3. Birthal, P. S., Hazrana, J., & Negi, D. S. (2022). Agricultural mechanization and its impact on farm productivity and rural labor use in India. *Indian Journal of Agricultural Economics, 77*(2), 189–205.
4. Raina, S., Joshi, A., & Pal, S. (2023). Determinants of digital technology adoption among smallholder farmers in India: A multi-state survey. *Indian Journal of Agricultural Economics, 78*(1), 45–67.

SMART FARMING TECHNOLOGIES FOR RESOURCE OPTIMIZATION AND AGRICULTURAL SUSTAINABILITY

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Abstract
The increasing global population, climate variability, depletion of natural resources, and rising food demand have intensified the need for sustainable agricultural systems. Smart farming technologies have emerged as transformative tools that improve agricultural productivity while ensuring efficient utilization of resources such as water, soil nutrients, energy, and labour. Technologies including the Internet of Things (IoT), artificial intelligence (AI), remote sensing, drones, precision agriculture, robotics, big data analytics, and decision support systems are revolutionizing traditional farming practices. These innovations enable real-time monitoring, data-driven decision-making, and automation, thereby reducing resource wastage and environmental degradation. This chapter discusses the role of smart farming technologies in resource optimization and agricultural sustainability. It highlights the applications, advantages, challenges, and future prospects of smart agriculture. The chapter also examines policy support, adoption barriers, and the importance of integrating digital technologies with sustainable agricultural practices to achieve food security and climate resilience.

Keywords: Smart Farming, Precision Agriculture, IoT, Artificial Intelligence, Sustainability, Digital Agriculture, Resource Optimization, Climate-Smart Agriculture.

1. Introduction

Agriculture remains the backbone of the global economy and continues to provide food, fiber, and livelihood security for billions of people worldwide. However, the agricultural sector is facing severe challenges due to rapid population growth, climate change, depletion of natural resources, soil degradation, declining biodiversity, and increasing food demand (FAO, 2021; United Nations, 2015). According to the Food and Agriculture Organization, global food production must increase substantially by 2050 to satisfy future food requirements while simultaneously ensuring environmental sustainability (FAO, 2021). Conventional farming systems are often characterized by inefficient resource utilization, excessive dependence on agrochemicals, and unsustainable irrigation practices, leading to ecological imbalance and reduced long-term productivity (Bongiovanni and Lowenberg-DeBoer, 2004).

In recent years, smart farming technologies have emerged as transformative approaches for modernizing agricultural systems and improving resource-use efficiency. Smart farming, also known as digital agriculture or Agriculture 4.0, integrates advanced technologies such as the Internet of Things (IoT), artificial intelligence (AI), machine learning, robotics, drones, cloud computing, remote sensing, and big data analytics into agricultural management systems (Wolfert *et al.,* 2017; Kumar *et al.,* 2024). These technologies facilitate real-time monitoring of crops, soil, weather conditions, irrigation, nutrient status, and pest incidence, thereby enabling precise and data-driven decision-making (Tzounis *et al.,* 2017).

Precision agriculture technologies have significantly improved input management by enabling site-specific application of water, fertilizers, and pesticides according to crop requirements (Gebbers and Adamchuk, 2010). Similarly, AI-driven predictive models assist farmers in forecasting yield performance, identifying crop diseases, and optimizing irrigation scheduling under variable climatic conditions (Liakos *et al.,* 2018). Remote sensing and drone-based imaging systems also provide high-resolution spatial information for crop monitoring and stress detection (Zhang and Kovacs, 2012).

Sustainable agriculture aims to achieve food security while preserving environmental quality, economic profitability, and social equity for future generations (Pathak *et al.,* 2019). Smart farming technologies contribute to sustainability by reducing greenhouse gas emissions, minimizing nutrient losses, conserving water resources, improving soil health, and increasing agricultural resilience against climate variability (Walter *et al.,* 2017; Bhatnagar *et al.,* 2024). Furthermore, digital agriculture supports the United Nations Sustainable Development Goals (SDGs), particularly those associated with zero hunger, climate action, responsible consumption, and sustainable production systems (United Nations, 2015).

The integration of smart technologies into agriculture is therefore increasingly recognized as a strategic solution for improving productivity and ensuring sustainable resource management under changing global environmental conditions (Aranguri *et al.,* 2025). This chapter discusses major smart farming technologies, their role in resource optimization, applications in sustainable agriculture, challenges in adoption, and future perspectives for achieving climate-resilient agricultural systems.

2. Concept of Smart Farming

Smart farming refers to the application of digital technologies and intelligent systems in agricultural production and management. It combines information and communication technologies with agricultural practices to improve efficiency and productivity.

The major objectives of smart farming include:

- Efficient use of agricultural resources
- Increased crop productivity

- Reduced environmental impacts
- Real-time monitoring and management
- Improved decision-making
- Enhanced sustainability and profitability

Smart farming is characterized by data-driven agriculture, automation, precision input application, and continuous monitoring of environmental and crop conditions. The emergence of Agriculture 4.0 has accelerated the adoption of smart technologies in farming systems.

The core components of smart farming include:

1. Internet of Things (IoT)
2. Artificial Intelligence (AI)
3. Big Data Analytics
4. Geographic Information Systems (GIS)
5. Remote Sensing
6. Robotics and Automation
7. Drones and UAVs
8. Cloud Computing
9. Decision Support Systems
10. Precision Agriculture Technologies

These technologies collectively enhance farm management and optimize resource utilization.

3. Need for Resource Optimization in Agriculture

Agricultural production depends heavily on natural resources such as land, water, energy, and nutrients. However, increasing pressure on these resources has created sustainability concerns.

3.1 Water Scarcity

Agriculture consumes approximately 70% of global freshwater resources. Inefficient irrigation methods lead to significant water losses through evaporation and runoff. Smart irrigation technologies help optimize water use through sensor-based irrigation scheduling and automated irrigation systems.

3.2 Soil Degradation

Excessive use of fertilizers and pesticides degrades soil quality and reduces biodiversity. Precision nutrient management techniques help maintain soil health by applying fertilizers based on crop requirements.

3.3 Energy Consumption

Modern agriculture requires substantial energy inputs for irrigation, machinery operation, and processing. Smart energy management systems and renewable energy integration improve energy efficiency.

3.4 Labor Shortages

Many countries face agricultural labour shortages due to urbanization and migration. Automation and robotics reduce dependency on manual labour and improve operational efficiency.

3.5 Climate Change

Climate variability affects agricultural productivity through droughts, floods, temperature fluctuations, and pest outbreaks. Smart farming technologies improve climate resilience through predictive analytics and climate monitoring.

Resource optimization is therefore essential for achieving sustainable agricultural systems and ensuring long-term food security.

4. Major Smart Farming Technologies

Advanced smart farming technologies have revolutionized modern agriculture by enabling data-driven management practices and automation of farming operations. These technologies improve efficiency, productivity, and sustainability through accurate monitoring and precise resource utilization (Klerkx *et al.,* 2019).

4.1 Internet of Things (IoT)

The Internet of Things (IoT) refers to interconnected physical devices embedded with sensors, software, and communication technologies that collect and exchange data over internet networks (Patel and Patel, 2019). In agriculture, IoT-based systems continuously monitor environmental parameters such as soil moisture, temperature, humidity, nutrient levels, and crop growth conditions (Khan *et al.,* 2025).

IoT applications in agriculture include smart irrigation systems, greenhouse automation, livestock monitoring, weather forecasting, and precision nutrient management (Khanna and Kaur, 2019). Sensor-based irrigation systems enable real-time soil moisture assessment and automated irrigation scheduling, thereby reducing water wastage and improving irrigation efficiency (Kumar *et al.,* 2024). Studies have demonstrated that IoT-assisted agriculture significantly enhances productivity while minimizing operational costs and environmental impacts (Ashir *et al.,* 2022).

4.2 Artificial Intelligence (AI)

Artificial intelligence has become one of the most influential technologies in modern agriculture due to its ability to analyse complex agricultural datasets and support intelligent decision-making processes (Javaid *et al.,* 2022). AI systems utilize machine learning algorithms, neural networks, and deep learning approaches to identify patterns and generate predictive insights from agricultural data.

AI technologies are widely applied in crop disease diagnosis, weed identification, yield prediction, irrigation scheduling, autonomous machinery, and precision spraying systems (Liakos *et al.,* 2018). AI-powered image recognition models can detect nutrient deficiencies and pest

infestations at early stages through drone imagery and smartphone-based diagnostics (Sharma *et al.,* 2024). Furthermore, predictive analytics generated through AI models improve climate adaptation and risk management in agriculture (Khan *et al.,* 2025).

4.3 Precision Agriculture

Precision agriculture refers to the site-specific management of agricultural inputs based on spatial and temporal variability within agricultural fields (Gebbers and Adamchuk, 2010). It integrates technologies such as Global Positioning Systems (GPS), Geographic Information Systems (GIS), remote sensing, yield monitoring systems, and variable rate technologies (VRTs) to optimize farm management (Balafoutis *et al.,* 2017).

Precision agriculture enables farmers to apply fertilizers, irrigation water, pesticides, and herbicides according to crop-specific requirements, thereby reducing excessive input application and improving resource-use efficiency (Bongiovanni and Lowenberg-DeBoer, 2004). Variable-rate fertilizer application systems have shown significant potential for reducing nutrient losses and improving soil fertility management (Lowenberg-DeBoer and Erickson, 2019).

4.4 Drones and Remote Sensing

Drones or unmanned aerial vehicles (UAVs) have gained substantial importance in precision agriculture due to their capability to capture high-resolution aerial imagery and real-time field information (Zhang and Kovacs, 2012). Drone-based remote sensing technologies support crop monitoring, disease detection, yield estimation, weed mapping, and precision spraying.

Remote sensing systems using multispectral and hyperspectral imaging help identify crop stress conditions, nutrient deficiencies, and water stress before visible symptoms appear (Gyamfi *et al.,* 2024). Such technologies improve decision-making efficiency and enable timely agronomic interventions. Satellite imagery integrated with GIS platforms further supports large-scale monitoring of agricultural landscapes and climate variability (Gemtou *et al.,* 2024).

4.5 Robotics and Automation

Agricultural robotics and automation systems are increasingly being adopted to address labour shortages and improve operational efficiency in farming systems (Walter *et al.,* 2017). Autonomous tractors, robotic harvesters, automated milking systems, and robotic weeders are examples of modern agricultural automation technologies.

Robotic systems perform repetitive farming operations with high precision and reduced human intervention, thereby minimizing labour costs and increasing productivity (Erickson and Fausti, 2021). Automated spraying systems also reduce pesticide usage by enabling targeted application based on weed recognition algorithms.

4.6 Big Data Analytics and Cloud Computing

The rapid growth of agricultural data generated through sensors, drones, satellites, and farm machinery has increased the importance of big data analytics and cloud computing in agriculture

(Wolfert *et al.,* 2017). Big data technologies facilitate collection, storage, processing, and interpretation of massive agricultural datasets.

Cloud computing platforms provide real-time access to farm information and support remote monitoring, decision support systems, and digital farm management solutions (Kamilaris *et al.,* 2017). Data-driven agriculture enables predictive analytics, precision management, and optimization of agricultural inputs under dynamic environmental conditions.

5. Applications of Smart Farming in Resource Optimization

5.1 Smart Irrigation Systems

Water scarcity is one of the most critical challenges in agriculture. Smart irrigation systems use sensors, weather data, and AI algorithms to optimize irrigation scheduling.

Benefits include:

- Reduced water wastage
- Improved water-use efficiency
- Enhanced crop productivity
- Lower energy consumption

Automated drip irrigation systems integrated with soil moisture sensors can significantly conserve water resources.

5.2 Precision Nutrient Management

Excessive fertilizer application contributes to soil degradation and water pollution. Precision nutrient management uses sensors and GIS mapping to determine nutrient requirements.

Benefits include:

- Reduced fertilizer costs
- Improved soil fertility
- Lower environmental pollution
- Increased nutrient-use efficiency

5.3 Pest and Disease Management

AI and remote sensing technologies detect pest infestations and diseases at early stages.

Benefits include:

- Reduced pesticide usage
- Targeted spraying
- Improved crop protection
- Lower environmental contamination

5.4 Livestock Monitoring

Smart livestock systems monitor animal health, feeding behaviour, and environmental conditions. Wearable sensors help detect diseases and improve animal welfare.

5.5 Greenhouse Automation

Smart greenhouses utilize sensors and automated systems to regulate temperature, humidity, lighting, and irrigation.

This improves crop quality and reduces resource consumption.

6. Smart Farming and Agricultural Sustainability

Agricultural sustainability involves maintaining productivity while protecting environmental resources and ensuring social and economic viability (Banerjee *et al.,* 2024).

Smart farming technologies support sustainability in several ways.

6.1 Environmental Sustainability

Smart agriculture reduces excessive use of fertilizers, pesticides, and water. Precision input application minimizes environmental pollution and conserves natural resources.

Benefits include:

- Reduced greenhouse gas emissions
- Improved soil health
- Conservation of water resources
- Reduced chemical contamination

6.2 Economic Sustainability

Smart farming improves farm profitability by reducing input costs and increasing productivity.

Benefits include:

- Higher crop yields
- Lower labour costs
- Reduced resource wastage
- Improved market competitiveness

6.3 Social Sustainability

Digital agriculture improves farmer decision-making and rural livelihoods.

It also creates opportunities for:

- Skill development
- Rural employment
- Knowledge sharing
- Improved food security

Smart farming technologies therefore contribute significantly to sustainable development goals (SDGs).

7. Challenges in Adoption of Smart Farming Technologies

Despite numerous benefits, adoption of smart farming technologies remains limited in many regions.

7.1 High Initial Investment

Smart farming equipment and digital infrastructure require substantial capital investment, which may not be affordable for smallholder farmers.

7.2 Lack of Technical Knowledge

Farmers often lack digital literacy and technical skills needed for operating advanced technologies.

7.3 Poor Internet Connectivity

Rural areas in developing countries often face limited internet access and digital infrastructure.

7.4 Data Privacy and Security

Collection and storage of agricultural data raise concerns regarding data ownership and cybersecurity.

7.5 Policy and Institutional Barriers

Limited government support, inadequate training programs, and weak extension services hinder technology adoption.

7.6 Small Farm Sizes

Fragmented land holdings reduce the economic feasibility of advanced technologies.

Addressing these challenges requires coordinated efforts from governments, researchers, private industries, and farmers.

8. Policy Support and Government Initiatives

Government policies play a crucial role in promoting digital agriculture.

Several countries have introduced programs supporting:

- Smart irrigation
- Precision farming
- Digital extension services
- Agricultural mechanization
- Climate-smart agriculture

International organizations such as FAO, OECD, and the World Bank promote smart agriculture through funding, policy frameworks, and research support.

The European Union's Green Deal and Farm-to-Fork strategy encourage sustainable and digital agriculture. In India, initiatives such as Digital Agriculture Mission, PM-KISAN, eNAM, and Smart Agriculture projects promote technological integration in agriculture.

Policy support should focus on:

- Subsidies for smart technologies
- Farmer training programs
- Rural internet infrastructure
- Research and development

- Public-private partnerships

9. Future Prospects of Smart Farming

The future of agriculture will increasingly depend on digital technologies and automation.

Emerging trends include:

- AI-driven autonomous farming
- Blockchain in supply chains
- Climate-smart agriculture
- Smart vertical farming
- Renewable energy integration
- Advanced robotics
- Digital twins in agriculture

Integration of artificial intelligence, IoT, robotics, and renewable energy systems will transform agriculture into a more resilient and sustainable sector (Ptak and Lis, 2024).

Future smart farms are expected to:

- Operate autonomously
- Use real-time predictive analytics
- Optimize resource utilization continuously
- Reduce environmental impacts significantly

The successful transition to smart agriculture requires inclusive policies, infrastructure development, capacity building, and affordable technologies.

Conclusion

Smart farming technologies have emerged as essential tools for improving agricultural productivity, optimizing resource utilization, and ensuring sustainability. Technologies such as IoT, AI, precision agriculture, drones, robotics, and big data analytics enable farmers to monitor agricultural operations accurately and make informed decisions. These technologies contribute significantly to water conservation, efficient nutrient management, reduced pesticide use, climate resilience, and environmental protection. Smart agriculture supports sustainable development by balancing economic profitability, environmental conservation, and social well-being.

However, challenges such as high costs, limited digital literacy, inadequate infrastructure, and policy constraints continue to hinder widespread adoption. Governments, researchers, industries, and farmers must collaborate to create supportive policies, improve rural connectivity, and provide training programs. The future of agriculture lies in the integration of advanced digital technologies with sustainable farming practices. Smart farming has the potential to transform global agriculture into a more efficient, resilient, and environmentally sustainable system capable of meeting future food demands.

References

1. Alreshidi, E. (2019). Smart sustainable agriculture (SSA) solution underpinned by Internet of Things (IoT) and Artificial Intelligence (AI). *arXiv Preprint*, arXiv:1906.03106.
2. Aranguri, M., Mera, H., Noblecilla, W., & Lucini, C. (2025). Digital literacy and technology adoption in agriculture: A systematic review of factors and strategies. *AgriEngineering, 7*(9), 296.
3. Ashir, D. M. N., Ahad, M. T., Talukder, M., & Rahman, T. (2022). Internet of Things (IoT) based smart agriculture aiming to achieve sustainable goals. *arXiv Preprint*, arXiv:2206.06300.
4. Balafoutis, A., Beck, B., Fountas, S., Vangeyte, J., Van der Wal, T., Soto, I., ... & Eory, V. (2017). Precision agriculture technologies positively contributing to GHG emissions mitigation, farm productivity and economics. *Sustainability, 9*(8), 1339.
5. Banerjee, N., Dambale, A. S., & Upadhyay, H. (2024). Smart farming technologies for sustainable agriculture. *Vol, 4*, 13–19.
6. Bhatnagar, S., Chaudhary, R., Sharma, S., Janjhua, Y., Thakur, P., Sharma, P., & Keprate, A. (2024). Exploring the dynamics of climate-smart agricultural practices for sustainable resilience in a changing climate. *Environmental and Sustainability Indicators, 24*, 100535.
7. Bongiovanni, R., & Lowenberg-DeBoer, J. (2004). Precision agriculture and sustainability. *Precision Agriculture, 5*, 359–387.
8. Erickson, B., & Fausti, S. (2021). Precision agriculture adoption and sustainability. *Agricultural Systems, 190*, 103091.
9. FAO. (2021). *The state of food and agriculture 2021*. Food and Agriculture Organization of the United Nations.
10. FAO. (2022). *Digital agriculture profile: India*. Food and Agriculture Organization of the United Nations.
11. Gebbers, R., & Adamchuk, V. I. (2010). Precision agriculture and food security. *Science, 327*(5967), 828–831.
12. Gemtou, M., Guillén, B. C., & Anastasiou, E. (2024). Smart farming technologies and sustainability. In *Digital sustainability: Leveraging digital technology to combat climate change* (pp. 99–120). Springer Nature Switzerland.
13. Gyamfi, E. K., ElSayed, Z., Kropczynski, J., Yakubu, M. A., & Elsayed, N. (2024). Agricultural 4.0 leveraging on technological solutions: Study for smart farming sector. *arXiv Preprint*, arXiv:2401.00814.
14. Javaid, M., Haleem, A., Khan, I. H., & Suman, R. (2023). Understanding the potential applications of Artificial Intelligence in agriculture sector. *Advanced Agrochem, 2*(1), 15–30.

15. Kamilaris, A., Kartakoullis, A., & Prenafeta-Boldú, F. X. (2017). A review on the practice of big data analysis in agriculture. *Computers and Electronics in Agriculture, 143*, 23–37.
16. Khan, M., Abbasi, S. F., Munir, M., Arshi, O., Latif, S., & Khan, I. U. (2025). Evolution of IoT in robotics. In *Artificial General-Internet of Things (AG-IoT) for Robotics: Advanced computer vision applications and future trends* (pp. 139–163). Springer Nature Switzerland.
17. Khan, S., Sachan, H. K., & Krishna, D. (2025). The role of smart farming technologies in mitigating climate change and enhancing agricultural sustainability. *International Journal of Environment and Climate Change, 15*(2), 138–159.
18. Khanna, A., & Kaur, S. (2019). Evolution of Internet of Things and its applications in agriculture. *Computer Communications, 144*, 92–108.
19. Klerkx, L., Jakku, E., & Labarthe, P. (2019). A review of social science on digital agriculture. *Agricultural Systems, 180*, 102763.
20. Kumar, V., Sharma, K. V., Kedam, N., Patel, A., Kate, T. R., & Rathnayake, U. (2024). A comprehensive review on smart and sustainable agriculture using IoT technologies. *Smart Agricultural Technology, 8*, 100487.
21. Liakos, K. G., Busato, P., Moshou, D., Pearson, S., & Bochtis, D. (2018). Machine learning in agriculture: A review. *Sensors, 18*(8), 2674.
22. Lowenberg-DeBoer, J., & Erickson, B. (2019). Setting the record straight on precision agriculture adoption. *Agronomy Journal, 111*(4), 1552–1569.
23. OECD. (2020). *Digital opportunities for better agricultural policies*. OECD Publishing.
24. OECD. (2021). *Agriculture and digital transformation*. OECD Publishing.
25. Patel, K. K., & Patel, S. M. (2019). Internet of Things-IOT: Definition, characteristics, architecture and applications. *International Journal of Engineering Science and Computing, 6*(5), 6122–6131.
26. Pathak, H., & Pal, S. (2019). Climate-smart agriculture in developing countries. *Agricultural Research, 8*(3), 145–156.
27. Ptak, A., & Lis, T. (2024). Digital transformation in manufacturing enterprises: The role and impact of IIoT. *Procedia Computer Science, 246*, 5214–5223.
28. Sharma, T., Mrabet, R., Singh, A., Kumar, N., Baghla, D., Kumar, S., ... & Chauhan, G. (2024). Global hunger: The need for smart and sustainable agriculture. In *Sustainable green nanotechnology* (pp. 129–151). CRC Press.
29. *Times of India*. (2025). *Smart tech beckons banana farmers*.
30. Tzounis, A., Katsoulas, N., Bartzanas, T., & Kittas, C. (2017). Internet of Things in agriculture. *Biosystems Engineering, 164*, 31–48.

31. United Nations. (2015). *Transforming our world: The 2030 agenda for sustainable development*. United Nations.
32. Walter, A., Finger, R., Huber, R., & Buchmann, N. (2017). Smart farming is key to developing sustainable agriculture. *Proceedings of the National Academy of Sciences, 114*(24), 6148–6150.
33. Wolfert, S., Ge, L., Verdouw, C., & Bogaardt, M. J. (2017). Big data in smart farming: A review. *Agricultural Systems, 153*, 69–80.
34. World Bank. (2019). *Harvesting prosperity: Technology and productivity growth in agriculture*. World Bank Publications.
35. World Economic Forum. (2022). *Innovation with a purpose: The role of technology innovation in accelerating food systems transformation*.
36. Zhang, C., & Kovacs, J. M. (2012). The application of small unmanned aerial systems for precision agriculture. *Precision Agriculture, 13*, 693–712.

RESIDUAL EFFECT OF HERBICIDES IN SOIL AND THEIR EFFECT ON ASSOCIATED AND SUCCEEDING CROPS

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Abstract
The widespread utilization of chemical herbicides in modern intensive agriculture has optimized weed management but raised critical concerns regarding long-term soil persistence and carry-over toxicity. Herbicide residues encompass the parent active ingredients along with their toxicological metabolites, conversion products, and impurities that remain within agricultural ecosystems. The structural longevity of these compounds, dictated by their half-life ($T_{1/2}$), is governed by complex interactions among chemical properties, environmental factors, and biological dynamics. This review synthesizes the key mechanics governing herbicide persistence, including adsorption, leaching, volatilization, and degradation kinetics. Furthermore, it details the adverse eco-toxicological consequences on non-target vegetation, soil microbiomes, faunal structures, and human health. State-of-the-art analytical frameworks and bioassay methodologies for monitoring residues are thoroughly evaluated. Finally, we explore diverse agronomic mitigation strategies—such as integrated weed management, specific crop rotations, organic amendments (farmyard manure and biochar), safeners, and advanced microbial bioremediation—to safeguard succeeding crops and preserve soil ecosystem sustainability.

Keywords: Herbicide Residues, Soil Persistence, Half-Life, Degradation Kinetics, Bioassay, Phytoremediation.

1. Introduction

Modern agricultural systems rely heavily on chemical weed control to achieve optimum yield potentials. However, the intensive application of these compounds frequently results in the accumulation of herbicide residues within the soil profile. Herbicide residues are formally defined as any specified substances in food, soil, agricultural commodities, and animal feed resulting from the use of a herbicide, inclusive of derivatives, metabolites, reaction products, and impurities of toxicological significance.

To minimize environmental hazards, an applied herbicide should ideally degrade efficiently after achieving its target objective. The length of time an active ingredient remains phytotoxic in the soil matrix defines its "soil persistence" or "soil residual life". Classifying herbicides by their relative persistence provides a baseline for evaluating carry-over risks to succeeding crops within rotational systems.

Table 1: Relative Persistence Profile of Major Herbicides in Soil Matrix

Persistence Period	Representative Herbicides
< 1 month	2,4-D, Glyphosate, MCPA
1–3 months	Alachlor, Acetochlor, Ametryn, Anilofos, Bispyribac-sodium, Butachlor, Carfentrazone-ethyl, Dalapon, Halosulfuron, Metribuzin, Metamifop, Metolachlor, Oxyfluorfen
3–6 months	Clomazone, Chlorimuron-ethyl, Diallate, Dithiopyr, Fluchloralin, Imazethapyr, Isoproturon, Metamitron, Oxadiazon, Linuron, Pendimethalin, Pyrazon
> 6 months	Atrazine, Bromacil, Chlorsulfuron, Diuron, Imazapyr, Picloram, Sulfentrazone, Sulfometuron, Simazine, Trifluralin, Paraquat

2. Environmental Fate and Dissipation Kinetics

Upon application, herbicides undergo several simultaneous physical, chemical, and biological transfer and dissipation processes.

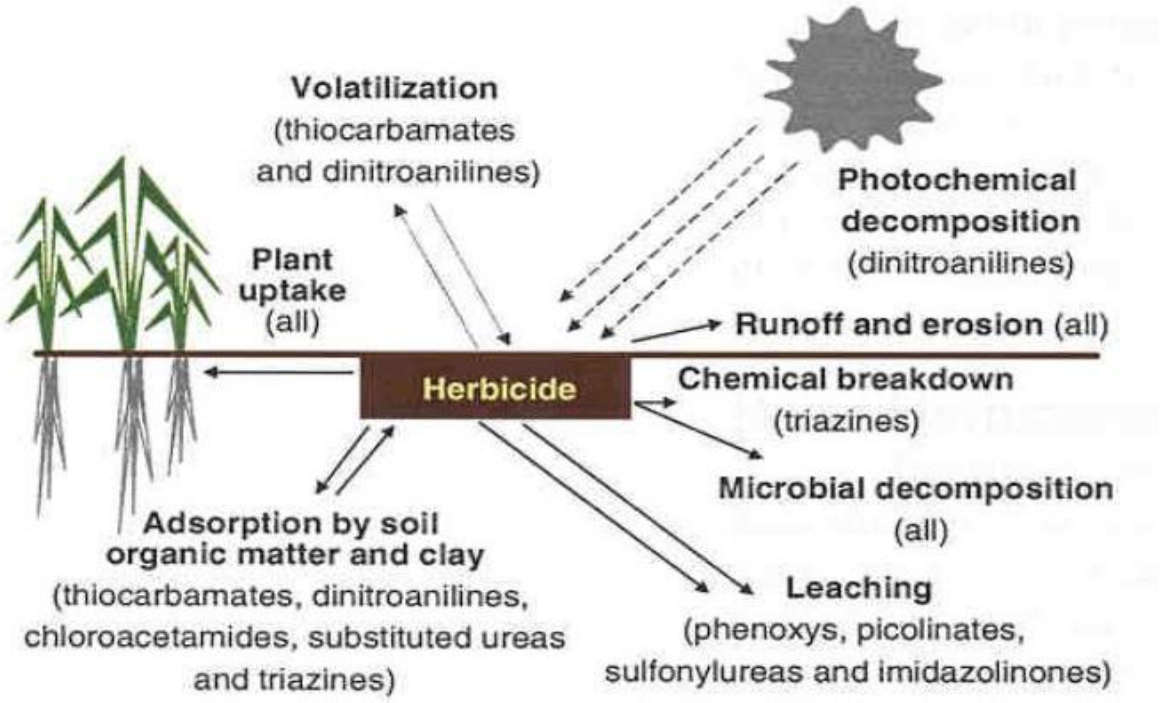

Figure 1: Schematic illustration of environmental fate and dissipation pathways of herbicides within the soil-plant ecosystem.

The standard metric used to predict persistence and dissipation behavior is the chemical half-life ($T_{1/2}$), which represents the time required for 50% of the initial herbicide concentration to degrade via physical or biochemical pathways.

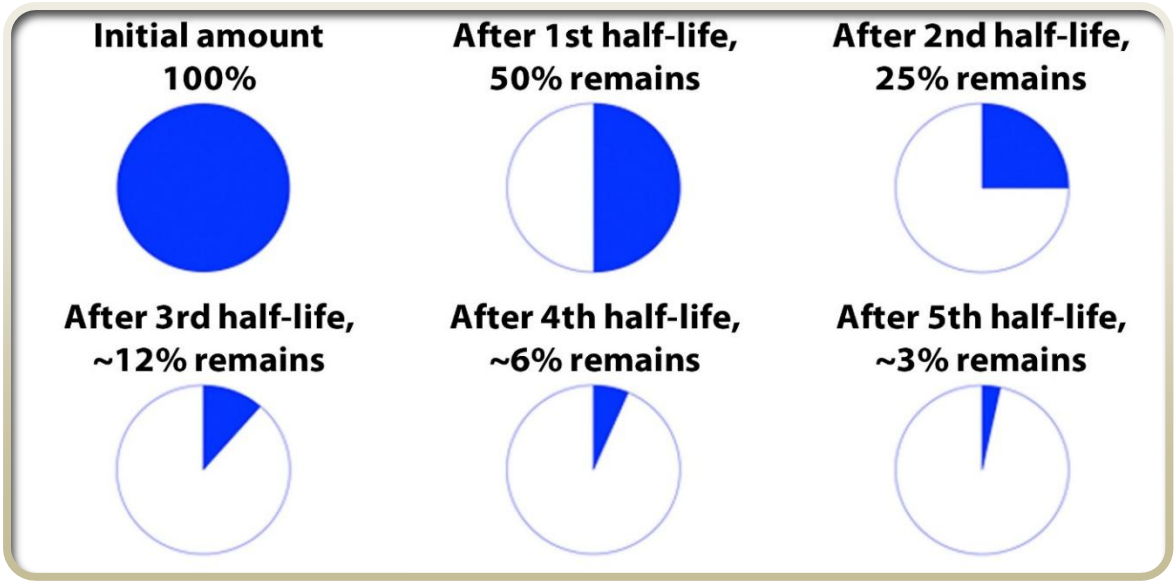

Figure 2: Visual model representing sequential chemical dissipation and fraction remaining across five successive half-life periods.

3. Factors Influencing Herbicide Carry-Over

The persistence and movement of herbicides in soils are regulated by three main factors: chemical characteristics, degradation pathways, and soil properties.

3.1 Herbicide Characteristics

- **Adsorption:** The binding affinity between herbicide molecules and soil particles. Strong adsorption limits down-profile mobility but can increase physical persistence within upper layers.
- **Water Solubility:** Highly water-soluble compounds move freely with soil water currents, increasing their susceptibility to deep leaching and dilution.
- **Volatilization:** The tendency of an active compound to transition into a gaseous state and escape into the atmosphere, which lowers its concentration in the soil.

3.2 Degradation Pathways

- **Microbial Decomposition:** The primary breakdown pathway, driven by soil microorganisms utilizing herbicides as substrates.
- **Chemical Degradation:** Abiotic processes, such as hydrolysis and oxidation, that break down chemical bonds.
- **Photodecomposition:** Ultraviolet radiation-driven cleavage of surface-applied herbicide molecules.

3.3 Soil Properties and Plant Uptake

- **Soil pH:** Strongly influences the ionization, solubility, and persistence of chemical families like the sulfonylureas and triazines.
- **Organic Matter & Texture:** High organic matter and clay fractions provide extensive

surface areas that bind herbicides, reducing immediate bio-availability while sometimes extending total persistence.

- **Moisture & Temperature:** Warm, moist soils enhance microbial metabolism and speed up abiotic reaction rates, leading to faster breakdown.
- **Plant Uptake Dynamics:** Dense plant populations absorb and metabolize substantial amounts of herbicide from the soil. Conversely, low plant populations leave higher residue concentrations behind.

4. Ecotoxicological Impacts of Residual Herbicides

Uncontrolled herbicide carry-over creates risks across multiple trophic levels within agricultural ecosystems.

4.1 Impact on Non-Target Plants and Succeeding Crops

Broad-spectrum persistent molecules can reduce biological diversity, disrupt ecological balances, and lower crop yields. They also make plants more vulnerable to opportunistic pathogens. Residual carry-over frequently damages sensitive succeeding crops grown in rotation.

4.2 Impact on Soil Health and Soil Fauna

Persistent active ingredients can degrade soil structure and disrupt organic matter transformation. They can also reduce soil microbial biomass and suppress critical functional groups like nitrifiers and mycorrhizae. Higher up the food chain, residues can affect animal populations, contributing to declines in sensitive bird species and localized fauna.

4.3 Human Health Hazards

Direct or indirect exposure to herbicide residues can cause acute and chronic health issues, including skin irritation and upper respiratory tract discomfort during handling or inhalation.

5. Methodologies for Herbicide Residue Quantification

Accurate monitoring requires precise analytical frameworks to quantify trace herbicide levels within soil and water matrices.

- **Gas Chromatography (GC / GC-MS):** The standard approach for volatile and semi-volatile compounds. It couples high-resolution separation with sensitive detection via electron capture or mass spectrometry.
- **Liquid Chromatography (HPLC / LC-MS):** Ideal for polar, non-volatile, or thermally unstable herbicides, offering high sensitivity and structural confirmation.
- **Spectrophotometry & TLC:** Useful screening tools that identify compounds based on characteristic light absorption or specific solvent migration values.
- **Bioassay Techniques:** A practical approach that measures the growth response of highly sensitive indicator plants to estimate bio-available residue levels.
- **ELISA & Electrochemical Methods:** Antibody-based tests and biosensors that offer rapid, highly specific screening directly in the field.

6. Agronomic Management and Mitigation Strategies

6.1 Integrated Weed Management and Crop Rotations

Integrated Weed Management (IWM) combines cultural, mechanical, and biological controls to minimize reliance on chemical inputs. Applying herbicides only when weed pressure passes economic thresholds helps lower total environmental chemical loads.

Properly planning crop rotations can prevent injury to sensitive succeeding crops. For example, while rapeseed and sugar beet are sensitive to imidazolinone residues, tolerant crops like maize, wheat, and barley can be safely integrated into the rotation.

Table 2: Recropping Restrictions for Sensitive Crops in Residual Soil Profiles

Herbicide Class / Active	Highly Sensitive Succeeding Crop Species
Sulfonylureas	Pea (*Pisum sativum*), Lentil (*Lens culinaris*)
Imidazolinones	Rapeseed (*Brassica napus*), Sugar beet, Sunflower
2,4-D	Tomato (*Solanum lycopersicum*)
Fluroxypyr	Wheat, Barley, Oats, Rye, Corn
Clopyralid	Corn, Flax, Canola, Mustard
Metosulam	Wheat, Lupins (*Lupinus* spp.)

Cultivating specialized herbicide-tolerant crops (e.g., specific mustard or berseem varieties for sulfosulfuron) also helps deplete soil residues by allowing plants to absorb and break down these compounds within their tissues.

6.2 Irrigation Interventions

Soil moisture levels play a critical role in herbicide breakdown rates by supporting active microbial communities. Controlled, light irrigation creates favorable conditions for microbial and chemical degradation without causing extensive leaching.

Table 3: Isoxaflutole Half-Life Dissipation Under Varying Soil Moisture Tensions at 25°C

Moisture Condition	Soil Water Potential (kPa)	Half-Life (T1/2 days)
Air Dry Soil	—	9.6
Very Dry	-1500 kPa	2.4
Adequate Moisture	-100 kPa	1.5

6.3 Organic Amendments and Adsorbents

Adding organic matter, such as farmyard manure (FYM) or biochar, enhances the soil's adsorption capacity. This binds free herbicide molecules and protects sensitive crops from immediate injury.

Table 4: Fluchloralin Residue Dissipation Profile over Time with Organic Amendments

Days After Application	Fluchloralin @ 1.0 kg/ha (Without FYM) (µg/g)	Fluchloralin @ 1.0 kg/ha + FYM @ 10 t/ha (µg/g)
1	0.484	0.406
7	0.352	0.231
15	0.252	0.158
30	0.104	0.053
At Harvest	0.004	0.001

Applying chemical safeners also helps protect crops by accelerating herbicide metabolism and detoxification within the plant tissues.

6.4 Optimized Application Techniques and Bioherbicides

- **Reduced Dosing & Split Applications:** Applying herbicides at the lowest effective dose or splitting applications reduces peak chemical concentrations in the soil and limits surface runoff.
- **Precision Placement:** Using banded applications instead of broadcast sprays targets weeds directly, reducing the total volume of chemical applied per unit area.
- **Natural Alternatives:** Incorporating allelochemicals and registered bioherbicides (e.g., Collego, Devine) reduces reliance on persistent synthetic chemistries.

6.5 Bioremediation Frameworks

Bioremediation uses living organisms to accelerate the breakdown of persistent compounds in the environment.

- **Biostimulation:** Adding tailored amounts of water, nutrients, or oxygen to boost the activity of native soil microorganisms capable of breaking down herbicides.
- **Bioaugmentation:** Introducing specific, highly efficient microbial strains into the soil. For example, introducing fungi like *Rhizopus oryzae* has shown success in accelerating the degradation of chloroacetamide herbicides like alachlor.
- **Phytoremediation:** Using tolerant plant species to extract, stabilize, or neutralize residual pollutants directly in the field. Success depends on matching the right tolerant plant variety with local soil conditions.

Conclusions

Herbicide residues present an ongoing challenge for sustainable crop rotations and environmental safety. Managing these residues effectively requires a clear understanding of how chemical properties, soil conditions, and degradation pathways interact. By combining precision application methods, organic amendments, and biological remediation techniques, growers can minimize carry-over risks, protect succeeding crops, and maintain long-term soil productivity.

References

1. Sarika, K., & Naidu, G. J. (2026). *Residual effect of herbicides in soil and their effect on associated and succeeding crops* (Unpublished draft). Department of Agronomy, Agricultural College, Bapatla, India.
2. FAO/WHO. (2019). *Submission and evaluation of pesticide residues data for the estimation of maximum residue levels in food and feed*. Food and Agriculture Organization of the United Nations.
3. Goring, C. A. I., & Hamaker, J. W. (1972). *Organic chemicals in the soil environment* (Vol. 1). Marcel Dekker.
4. Moyer, J. R. (1995). Effect of soil-applied herbicides on subsequent crops. *Journal of Crop Production*, 4(1), 103–134.
5. Weber, J. B., Shea, P. J., & Wilkerson, S. B. (2000). Soil topographic and agronomic factors affecting herbicide persistence and movement. *Agronomy Journal*, 92(4), 579–588.
6. Gustafson, D. I. (1989). Groundwater ubiquity score: A simple method for assessing pesticide leachability. *Environmental Toxicology and Chemistry*, 8(4), 339–357.
7. Kah, M., & Brown, C. D. (2006). Adsorption and degradation of weak polymeric acids in soils. *Journal of Environmental Quality*, 35(3), 745–754.
8. Alexander, M. (1999). *Biodegradation and bioremediation* (2nd ed.). Academic Press.
9. Sebire, M., Budzinski, H., & Baird, D. J. (2011). Ecotoxicological impacts of agricultural pesticide residues on non-target soil organisms. *Ecotoxicology*, 20(5), 981–993.
10. Damalas, C. A., & Eleftherohorinos, I. G. (2011). Pesticide exposure, safety issues, and risk assessment indicators. *International Journal of Environmental Research and Public Health*, 8(5), 1402–1419.
11. Tadeo, J. L. (2008). *Analysis of pesticides in food and environmental samples*. CRC Press.
12. Horowitz, M. (1976). Application of bioassay techniques for determination of herbicide residues in soil. *Weed Research*, 16(5), 301–315.
13. Liebman, M., Mohler, C. L., & Staver, C. P. (2001). *Ecological management of agricultural weeds*. Cambridge University Press.
14. Jones, D. L., Edwards-Jones, G., & Murphy, D. V. (2011). Biochar mediated alterations in herbicide behavior in agricultural soils. *Soil Biology and Biochemistry*, 43(6), 1192–1201.
15. Singh, D. K. (2008). Biodegradation and bioremediation of pesticide residues in soil. *Indian Journal of Microbiology*, 48(1), 35–44.

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THE POLICY FRAMEWORKS AND DIGITAL TOOLS RESHAPING MODERN AGRICULTURE

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Abstract

Modern agriculture is undergoing a radical transformation driven by digital innovation, climate crises, and mounting demographic and environmental pressures. This study examines the conceptual shift from traditional farming methods to "Smart Agriculture" (Agriculture 4.0), which integrates the Internet of Things (IoT), artificial intelligence (AI), drones, and automated systems to transition field management from broad guesswork to real-time, micro-zoned precision. Backed by an institutional framework of national digital missions, equipment subsidies, and international sustainability guidelines, these technologies serve as direct productivity multipliers. Empirically, smart farming practices increase crop yields by 15% to 20%, lower water consumption by up to 50%, reduce synthetic input runoffs by 35%, and expand farmers' net profit margins by 15% to 18.5%. Despite these measurable economic and ecological dividends, the widespread scaling of data-driven ecosystems faces critical socio-technical bottlenecks. These challenges include high upfront capital investments, low digital literacy among aging demographics, rural connectivity gaps, and unresolved data privacy risks. Ultimately, this paper outlines a strategic roadmap emphasizing public-private partnerships, decentralized infrastructure, localized training hubs, and interoperable, eco-friendly technology standards to foster an equitable, resilient, and universally accessible modern agricultural standard.

Keywords: Smart Agriculture, Precision Farming, Internet of Things (IoT), Digital Public Infrastructure (DPI), Agricultural Productivity.

Introduction

Agro-Development is under radical transformation from fast pace of development in digital innovation, climate crisis consciousness, demographic multiplication and increasing load on environment or expanding stress on planetary systems. Native agricultural methods and community-based methods are being gradually overtaken by technologically advanced means of farming that integrate information technology such as Internet of Things (IoT), drones, sensors, robotics and data analytics in the frameworks of farming systems that organize structures for cultivation. Intelligent agriculture seeks to raise production, make more efficient use of

resources, maintain ecological health, and boost farmers' incomes. A range of governments and policymakers in various regions promote smart agriculture through digital policies, subsidies, training programs, precision farming initiatives, and sustainable agricultural frameworks. The smart farming technologies enable the farmers to observe the condition of their soil, to make necessary irrigation adjustments, to forecast the diseases that crop with the proper chemical use will be faced down, and to manage their supply chains effectively. This chapter presents the idea of smart agriculture through analyzing policy environment, modern agricultural practices, technical advancements, implementation obstacles and future prospects. Research methodology, its findings and recommendations for sustainable agricultural development are discussed.

1.1 Smart Agriculture: Conceptual Framework

Smart Agriculture (also known as Smart Farming or AgriTech) is the application of modern Information and Communication Technologies (ICT) to agriculture. It is a management concept aimed at preparing agricultural organizations to utilize sophisticated technology such as the Internet of Things (IoT), sensors, robotics, and Artificial Intelligence (AI) to track, monitor, automate, and analyze agricultural operations. The objective is to increase crop quality and quantity while reducing the amount of human labor and resources (which include water, fertilizers, and fuel). Rather than a whole field being treated uniformly, smart agriculture allows farmers to micro-manage individual square meters of land or even individual plants.

Agriculture has evolved through distinct eras, with each stage marked by a massive leap in technology and productivity:

Agriculture 1.0 (Traditional Farming)

Up to early 20th Century

Dependent exclusively on intensive manual human labor, draft animals and simple tools. Decisions were heavily influenced by historical weather patterns, intuition, and generational folklore. The yield was very low in many places and very vulnerable to pests and weather shocks.

Agriculture 2.0 (The Green Revolution)

1950s - late 20th Century

Defined by combustion-engine machinery (tractors, combines), synthetic chemical fertilizers, pesticides, and high-yielding, genetically modified crop varieties. Productivity flourished. But it was at a great environmental cost and inefficiency to manage the resources.

Agriculture 3.0 (Precision Agriculture)

Early 2000s

With GPS technology farmers were able to map fields precisely. Tractors could steer by guidance features to avoid overlapping rows. Though data collection started here, most of the analysis was done after the season had ended, not in real time.

Agriculture 4.0 (Smart Agriculture)

Present Day

The current era. Powered by constant connectivity, cloud computing, and automated decision-making. Devices don't simply collect data for humans to read later, they speak with one another in real time, allowing systems to automatically change irrigation or issue alerts based on AI predictions.

The fundamental difference lies in how decisions are made and how resources are applied. Traditional farming views a field as a single, homogenous unit; smart farming views it as a collection of unique micro-zones.

Table 1: Traditional vs. Smart Farming

Feature	Traditional Farming	Smart Farming
Decision Base	Intuition, weather forecasts, and historical habits.	Real-time sensor data, satellite imagery, and AI models.
Resource Allocation	Uniform application of water, seeds, and fertilizer across the whole field.	Variable-rate application; inputs are given only where and when needed.
Labor Profile	High reliance on manual physical labor and constant field scouting.	High reliance on automated machinery, remote monitoring, and software systems.
Environmental Impact	Higher risk of chemical runoff, soil degradation, and water waste.	Lower footprint via targeted chemical application and water conservation.
Risk Management	Reactive (treating a crop disease *after* it spreads across the field).	Predictive (using humidity sensors to predict and prevent mold before it hits).

1.2 Need for Smart Agriculture

The immediate shift to smart agriculture is prompted by a growing resource and demand crisis. With global populations marching toward nearly 10 billion by 2050, traditional farming systems can no longer keep up, confronting extreme, unpredictable weather and severe environmental degradation from decades of chemical over-reliance. Adding to this complexity is the fact that agriculture uses roughly 70% of the planet's freshwater and that we have critical global labor shortages as young people are moving away from rural fields. Smart agriculture addresses this crisis by substituting broad guesswork with precision data and increasing farmers' ability to grow vastly more food, requiring drastically less water, targeted fertilizers, and automated labor, transforming farming from an ecological strain into a sustainable, resilient system.

1.3 Policy Frameworks for Smart Agriculture

Smart agriculture is being implemented, and the drive to adopt it is fundamentally induced and further promoted by an institutionally structured policy framework that takes advantage of technology in agriculture. National Agricultural Policies set the long-term vision at the foundational level by integrating technological innovations into national strategies for climate

resilience and productivity. This vision is realised in Digital Agriculture Missions, which establish the necessary "Digital Public Infrastructure" in the form of AgriStack, digital farmer IDs, and geospatial hubs to unite farming data and deliver AI advisories and digital financial services. To ease the capital cost of these technologies, governments provide targeted Subsidies and Incentives that help smallholder farmers by paying directly for expensive high technology machinery components such as agricultural drones and smart irrigation systems. Finally, these domestic projects are grounded in International Sustainability Frameworks (e.g. FAO's Climate-Smart Agriculture guidelines and UN SDGs) to ensure that local domestic digital innovations find the right mix and match commercial productivity with global climate mitigation and environmental protection.

1.4 Smart Agricultural Practices

Table 2: The core modern practices defining smart agriculture, how they work, and their main benefits.

Practice	How It Works	Big Benefit
Precision Farming	Uses GPS, drones, and soil sensors to target specific spots in a field rather than treating the whole area uniformly.	Eliminates waste by applying inputs (seeds, fertilizer) only where needed.
Smart & Drip Irrigation	Delivers water directly to plant roots via a network of valves that open and close based on real-time soil moisture data.	Saves up to 50% more water compared to traditional flooding methods.
Organic & Sustainable Farming	Combines natural biological cycles with AI data to track soil health, rotate crops efficiently, and manage pests naturally.	Restores long-term soil health and biodiversity without chemical dependency.
Greenhouse & Vertical Farming	Grows crops indoors in stacked layers under fully controlled LED lighting, temperature, and nutrient-rich water loops.	Produces 10x to 30x higher yields per square foot, completely immune to outdoor weather.

1.5 Role of Technology in Agriculture

Modern tech is turning fields into digital data hubs. By processing live data streams, farmers can automate heavy labor, predict crop issues, and treat every single plant with pinpoint accuracy.

1.6 Benefits of Smart Agriculture

Smart agriculture turns operational information into economic and ecological dividends. This approach allows farmers to monitor data on crop health and soil parameters to optimize crop conditions efficiently, leading to vastly increased crop productivity and overall yields. This data-led real-time implementation ensures more effective use of water and fertilizer because automatic systems only use inputs where and when necessary, thus eliminating broad-blanket waste. Because of this target precision we are able to substantially reduce the environmental

impact by avoiding toxic chemical runoff into nearby water tables and preventing soil degradation. Ultimately, it's all about better decision-making, brought by data analytics replacing guesswork with predictive, real-time insights and giving farmers the ability to manage risks whether they arise from pest outbreaks or changing weather patterns before the issues affect the bottom line.

Table 3: Technology driven farming solution's

Technology	Core Role in Farming	Real-World Use Case
Internet of Things (IoT)	Continuous data collection and cross-device communication.	Soil sensors automatically telling water valves to turn on.
Artificial Intelligence (AI)	Pattern recognition, prediction, and decision-making.	Computer vision identifying a specific weed or predicting harvest yields.
Drones & Satellites	High-altitude field scanning and aerial mapping.	Spotting nitrogen deficiencies or pest outbreaks across a 500-acre field.
Agricultural Robotics	Automating physically demanding and precise field tasks.	Autonomous bots weeding vegetable rows or robot arms picking delicate fruit.

1.7 Challenges in Smart Agriculture

While smart agriculture offers revolutionary benefits, transitioning from a traditional farm to a data-driven ecosystem comes with a distinct set of practical hurdles.

Table 4: Core Challenges in Implementing Smart Agriculture

Challenge	Root Cause	Practical Impact on the Farm	Potential Solution
High Initial Investment	Advanced hardware (drones, RTK-GPS tractors) and proprietary software licenses carry steep upfront costs.	Small and marginal farmers are priced out, risking a "digital divide" where only large corporate farms can compete.	Government subsidies, pay-as-you-go tech rentals, and cooperative equipment sharing.
Lack of Digital Literacy	The aging demographic of global farmers means many are highly skilled in agronomy but unfamiliar with cloud software or data dashboards.	Farmers may misinterpret data dashboards, underutilize expensive tools, or entirely resist transitioning away from traditional habits.	Peer-to-peer training networks, simplified multilingual app UIs, and specialized local agritech consultants.

Connectivity & Infrastructure	Smart farming requires stable, high-speed internet (4G, 5G, or LoRaWAN) to transmit live data, but rural farming zones often have poor coverage.	Sensors fail to send real-time alerts, autonomous machinery loses connection mid-field, and cloud-based AI tools become unusable.	Expanding rural cellular networks, deploying offline-first edge computing devices, and utilizing low-Earth-orbit satellite internet (e.g., Starlink).
Data Privacy & Cybersecurity	Farm data (yield sizes, field boundaries, financial logs) is uploaded to third-party cloud servers with unclear ownership laws.	Hackers could breach smart networks to lock automated systems (ransomware), or big tech corporations could monetize private farm data to manipulate market pricing.	Enforcing strict agricultural data protection laws (like the open-source Ag Data Transparent standard) and implementing encrypted decentralized storage.

2. Objectives of the Study

- To unpack the definition of smart agriculture and demonstrate how data-driven precision fundamentally secures global food supplies against mounting ecological pressures.
- To evaluate how national digital missions, targeted equipment subsidies, and international frameworks incentivize farmers to adopt tech-driven practices.
- To explore how the integration of IoT sensors, AI analytics, remote sensing, and robotics automates farm labor and replaces historical guesswork with real-time insights.
- To balance the measurable resource savings and yield increases of smart farming against major hurdles like high upfront costs, rural connectivity gaps, and data privacy risks.
- To provide actionable strategies such as low-cost open-source tools, digital literacy programs, and eco-friendly tech standards to foster equitable and sustainable agricultural growth.

3. Data and Methodology

3.1 Research Design

Descriptive and analytical research are used in the study. The descriptive aspect is employed to watch, record, and map out the current field of smart agriculture adoption, detailing exactly which technologies are currently utilized, by whom and at what rate. The analytical part delves deeper into cause-and-effect, finding out how and why that cause is so, explaining the technological barriers to adoption and how certain parameters (such as data-driven insights) can

translate directly to improved or less promising agricultural outcomes in comparison with traditional approaches.

3.2 Sources of Data

The study is grounded and academically robust to which data collection will fall from two kinds of sources:

- **Primary Data:** Collected from actual fieldwork through direct access to agricultural stakeholders. It does have the ability to provide real-time unmediated operational details, crop yield information, and actual ground challenges.
- **Secondary Data:** Obtained from existing published documents that give macro-level context, historical references, and validated legal/policy structures. That includes peer-reviewed academic journals, official government reports, agricultural census data, and articles published by international sustainability organizations (such as the FAO).

3.3 Sampling Technique

In the end, the inability to analyze all farms in the same manner led the research to use stratified random sampling and purposive sampling. To ensure that each farm is represented equally, however, the farming population is stratified (divided) into subgroups based on farm size (smallholder versus large-scale) and technology adoption level (traditional versus smart-equipped). In contrast, purposive sampling is used to select agritech experts, agricultural scientists, and policymakers who possess specialized, high-level knowledge relevant to the study.

3.4 Data Collection Methods

Data is captured using a three-pronged collection strategy to ensure that quantitative numbers are completely backed by qualitative human context.

Table 5: Field Collection Matrix

Collection Tool	Primary Target Group	Type of Information Captured
Structured Questionnaires	Active Field Farmers (Traditional & Smart)	Quantitative data: Cost savings, exact water usage, crop yield totals, and digital literacy ratings.
Semi-Structured Interviews	Agricultural Tech Experts & Policymakers	Qualitative data: Systemic infrastructure limits, policy execution gaps, and future technology roadmaps.
Direct Field Observations	Active Smart Farming Sites	Physical verification: Machinery usability, drone deployment limits, and real-time sensor performance.

3.5 Analytical Tools and Techniques

Once data collection is complete, the raw information is processed using three core analytical methods:

- **Statistical Analysis:** Quantitative survey data is run through statistical tools to discover clear trends, calculate averages, and map percentages regarding yield growth and resource minimization.
- **Comparative Analysis:** Directly contrasts data blocks from traditional farms against smart farms to precisely measure differences in input efficiency (water, fertilizer, seed waste), labor hours, and overall profitability.
- **Case Study Method:** Focuses heavily on a select few specific farms that have either completely succeeded or failed in their smart transition, offering a narrative deep-dive into practical "dos and don'ts."

3.6 Scope and Limitations of the Study

Every research project operates within realistic boundaries. Defining these parameters ensures the final insights are interpreted with the right context:

- **Geographic & Thematic Scope:** Geographically, the study is confined to specific regional agricultural belts actively undergoing digital modernization. Thematically, it isolates the impacts of IoT sensors, remote sensing, AI diagnostics, and robotics, excluding non-digital upgrades like basic mechanical plow improvements.
- **Research Limitations & Constraints:** The study must account for rural data fragmentation, as many traditional smallholders do not keep rigorous written financial ledgers, requiring reliance on memory. Additionally, extreme localized weather anomalies (like a sudden drought or unseasonal flood) during the study window could temporarily warp typical seasonal data trends.

Table 6: Scope and Boundaries Summary

Dimension	Boundaries of the Study	Acknowledged Constraints
Research Scope	Regional farming clusters adopting digital tools (IoT, drones, smart irrigation) for crop management.	Excludes industrial-scale forestry, deep-sea aquaculture, and pure livestock processing complexes.
Research Limitations	Dependency on self-reported farmer memory for historical cost and yield comparisons.	Highly localized soil and weather variables mean findings cannot be universally applied to every climate globally.

4. Results and Discussion

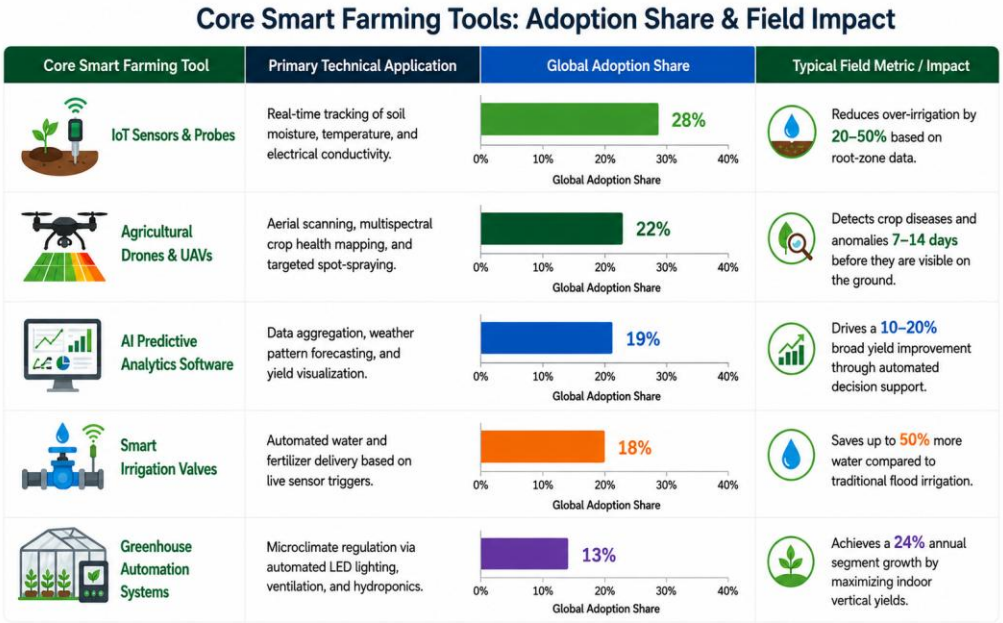
4.1 Adoption of Smart Agricultural Technologies

Worldwide adoption of smart agricultural techniques has exploded, converting the old farmlands into data-driven settings to meet rising food demands. Although large-scale commercial organizations are now pushing ahead with IoT-compatible automated machinery in their fields, small and medium size farms are incorporating low-cost applications for mobile data, modular IoT configuration, and regional sensor network. Top smart farming tools used all over the world

include IoT soil and weather sensors for the live monitoring of microclimates, multispectral agri drones and satellites which are able to detect crop stress early with NDVI mapping, and intelligent irrigation systems which avoid water waste. In tandem, these linked technologies create an integrated digital ecosystem that replaces historical guesswork with operational accuracy in real time.

Table 7: Global Smart Agriculture Tools Adoption

Core Smart Farming Tool	Primary Technical Application	Global Adoption Share	Typical Field Metric / Impact
IoT Sensors & Probes	Real-time tracking of soil moisture, temperature, and electrical conductivity.	**28%**	Reduces over-irrigation by **20–50%** based on root-zone data.
Agricultural Drones & UAVs	Aerial scanning, multispectral crop health mapping, and targeted spot-spraying.	**22%**	Detects crop diseases and anomalies **7–14 days** before they are visible on the ground.
AI Predictive Analytics Software	Data aggregation, weather pattern forecasting, and yield visualization.	**19%**	Drives a **10–20%** broad yield improvement through automated decision support.
Smart Irrigation Valves	Automated water and fertilizer delivery based on live sensor triggers.	**18%**	Saves up to **50%** more water compared to traditional flood irrigation.
Greenhouse Automation Systems	Microclimate regulation via automated LED lighting, ventilation, and hydroponics.	**13%**	Achieves a **24%** annual segment growth by maximizing indoor vertical yields.



4.2 Impact on Agricultural Productivity

Smart farm technologies act as a direct multiplier in agricultural productivity and systematically restructure the farm's balance sheet. By applying centimeter-level data instead of historical guesswork, farmers can achieve a significant boost in crop yield in the range of 15% to 20%, by having mathematically optimized growing conditions and halting disease outbreaks days before they manifest. This is accompanied by massive optimization of resources: Automation reduces water waste by up to 50% with targeted drip systems, and synthetic input loads are decreased by applying fertilizers only where soil sensors show an active deficiency. Thus, high harvest volumes together with focused input reductions bring a strong cost reduction, consistently increasing net profit margins by 15% to 18.5% and turning agriculture into a highly efficient business model.

4.3 Role of Government Policies

Government policies serve as the primary institutional engine driving the transition from traditional farming to data-driven precision ecosystems. By providing financial safety nets, creating foundational digital infrastructure, and heavily lowering upfront hardware costs, legislative frameworks directly influence the pace of modern agritech integration.

Table 8: Policy Frameworks: Impact and Structural Bottlenecks

Policy Core Component	Primary Intent & Target Schemes	Measured Effectiveness & Success	Critical Implementation Challenges
Digital Public Infrastructure (DPI)	AgriStack & Digital Farmer IDs: Building a centralized database for seamless land verification, credit access, and target allocations.	More than 9.17 crore unique Farmer IDs generated, standardizing direct land-mapping data across regional sectors.	Data Privacy Risks: Lack of transparent local data-governance laws raises concerns over big-tech monetization and unauthorized field profiling.
Direct Equipment Subsidies	Sub-Mission on Agricultural Mechanization (SMAM): Providing 40% to 80% cost-reimbursements on advanced hardware like laser land levelers.	Over 21.6 lakh smart machines were distributed; enabled the creation of thousands of village-level Custom Hiring Centers (CHCs).	Administrative Red Tape: Slow processing pipelines and delayed subsidy reimbursements leave cash-strapped smallholders waiting months for refunds.

Targeted Technology Inclusions	Namo Drone Didi Scheme: Training 15,000 women-led self-help groups to operate drones for nano-fertilizer and pesticide application.	Diversifies rural income streams by an average of ₹1 lakh annually per group while lowering aggregate pesticide exposure.	The Connectivity Bottleneck: A massive lack of rural 4G/5G coverage or stable electrical micro-grids renders advanced connected devices unusable.
Climate and Water Governance	Per Drop More Crop (PDMC) Scheme: Subsidizing the installation of smart micro-irrigation, automated drip lines, and field sprinklers.	Replaced broad-blanket field flooding, driving an average 30% to 50% water-saving margin across participating arid belts.	Maintenance Gaps: High operational costs and a severe shortage of localized technical service mechanics lead to quick equipment abandonment.
Risk and Income Mitigation	PM Fasal Bima Yojana (PMFBY): Utilizing satellite imaging and AI-based pest surveillance networks for automated crop damage validation.	Transitions insurance claims away from human error; uses the National Pest Surveillance System for predictive risk defense.	Socio-Economic Exclusions: Tenant and lessee farmers often lack formal land registry titles, locking them completely out of automated insurance portals.

4.4 Socio-Economic and Environmental Impact

Smart agriculture shifts the dynamics for more productive cycles and a positive cyclic effect reaching well beyond the field of farming and remaking rural economics and natural ecology. Meanwhile, the combined effect of higher crop yields and lower operating cost directly increases profit margins, resulting on average in farmers' net income increasing 18.5% to 22%, and insulates smallholder households from abrupt market disturbances. At the same time, as automation cuts back on long hours of grueling manual field labor, it is reconstituting the rural labor market by creating high-value occupations for tech-related professions think, local drone pilots, data technicians, agritech maintenance workers, etc. The net result is significantly healthier rural economies that benefit from reduced reliance on farming and farming-related production loss. Importantly, the shift does deliver great environmental sustainability through predictive data and computer vision based spot-treat instead of blanket chemical to treat fields smart farming reduces synthetic fertilizer and pesticide runoff by up to 35% and so protects local water tables, preserves critical soil microbiology, and reduces the global food systems' carbon footprint.

4.5 Future Prospects and Recommendations

To transition smart agriculture from a series of isolated, high-tech success stories into an accessible, nationwide farming standard, the industry must shift toward systematic scalability. Addressing existing infrastructure, digital literacy, and financial barriers requires a coordinated approach across multiple sectors.

Table 9: Strategic Roadmap: Future Prospects and Recommendations

Strategic Pillar	Core Action Item	Implementation Mechanism	Expected Long-Term Outcome
Expansion of Digital Infrastructure	Bridge the rural connectivity divide through targeted telecom investments.	Deploy low-power LoRaWAN networks for cheap sensor communication. Leverage low-Earth-orbit satellites (e.g., Starlink) in deep rural dead zones. Build solar-powered local electrical micro-grids.	Guarantees continuous, real-time data transmission for automated irrigation, machinery telemetry, and live crop alerts without network drops.
Farmer Training & Awareness Programs	Institutionalize digital literacy and hands-on technical education.	Establish village-level Krishi Vigyan Kendras (KVKs) as agritech demo hubs. Launch multilingual, voice-guided AI farm assistants via WhatsApp/mobile apps. Host interactive peer-led field workshops.	Eliminates user anxiety, replaces generational habits with data-driven confidence, and reduces user-error tech abandonment.
Public-Private Partnerships (PPP)	Create shared-risk financial models and localized service channels.	Scale the Farming-as-a-Service (FaaS) model for pay-per-use drone fleets. Provide state-backed credit guarantees to agritech startups. Open co-funded regional maintenance and repair centers.	Allows resource-poor smallholders to access advanced robotics and drones on a flexible budget without taking on high, personal upfront debt.
Sustainable Agricultural Innovation	Incentivize eco-friendly, open-source, and interoperable technology.	Enforce universal open API data standards across tractor and sensor brands. Invest in biodegradable hardware and solar-powered field sensors. Tie tech metrics directly to global carbon-credit registries.	Prevents restrictive vendor lock-in, reduces electronic waste, and rewards farmers financially for actively practicing verifiable carbon sequestration.

Conclusion

Smart agriculture is the future of farming — it integrates cutting-edge technologies with efficient farming practices and is backed by supportive policy frameworks. Precision farming, IoT devices, AI-based analytics, drones, and automated irrigation systems all support the increase in farming output while conserving natural resources. Successful implementation needs strong government support, farmer awareness, affordable technologies, rural digital infrastructure, and effective policy execution. Smart agriculture helps not just with food security but with environmental sustainability and rural economic growth. Ultimately, for the future development of the agriculture sector, the pace of development will largely depend on how far nations can get technology, policy, and sustainable farming models to be embedded into a coherent agricultural ecosystem.

References

1. European Commission. (2020). *Smart farming and sustainable agriculture*. European Commission.
2. Food and Agriculture Organization (FAO). (2022). *Digital technologies in agriculture and rural areas*. FAO.
3. Klerkx, L., Jakku, E., & Labarthe, P. (2019). A review of social science on digital agriculture. *NJAS - Wageningen Journal of Life Sciences*.
4. Liakos, K., et al. (2018). Machine learning in agriculture. *Sensors, 18*.
5. Ministry of Agriculture and Farmers Welfare, Government of India. (2021). *Digital Agriculture Mission 2021–2025*. Ministry of Agriculture and Farmers Welfare.
6. OECD. (2019). *Innovation, agricultural productivity and sustainability*. OECD Publishing.
7. Patel, N., & Shah, R. (2020). IoT applications in smart agriculture. *International Journal of Computer Applications*.
8. Reddy, G. P. (2021). *Sustainable agriculture and smart farming*. Scientific Publishers.
9. Sharma, P., & Verma, S. (2021). Smart irrigation systems for sustainable agriculture. *International Journal of Agricultural Research*.
10. Singh, R. (2022). Role of Artificial Intelligence in modern agriculture. *Journal of Agricultural Science*.
11. UNESCO. (2021). *Technology and rural development report*. UNESCO.
12. United Nations. (2023). *Sustainable Development Goals report*. United Nations.
13. Wolfert, S., Ge, L., Verdouw, C., & Bogaardt, M. (2017). Big data in smart farming. *Agricultural Systems, 153*, 69–80.
14. World Bank. (2021). *Agriculture and food: Transforming food systems*. World Bank.
15. Zhang, Q. (2015). *Precision agriculture technology for crop farming*. CRC Press.

NON-SPINNING SYNDROME IN SILKWORMS: AN EMERGING PHYSIOLOGICAL CATASTROPHE AND BIOTECHNOLOGICAL FRONTIER IN CONTEMPORARY SERICULTURE

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Abstract

Sericulture, an exquisitely sophisticated agro-biological enterprise underpinning rural socio-economic sustainability and natural silk production, is presently encountering an increasingly catastrophic physiological anomaly designated as Non-Spinning Syndrome (NSS) in the mulberry silkworm, *Bombyx mori* L. The syndrome is characterized by the conspicuous inability of physiologically mature larvae to initiate, sustain, or consummate cocoon spinning, thereby precipitating severe deterioration in cocoon productivity, filament integrity, reelability, and commercial silk recovery. The etiopathogenesis of NSS is profoundly multifactorial, encompassing genetic aberrations, endocrine dysregulation, pathogenic invasions, nutritional inadequacies, toxicological contamination, and environmental perturbations. Mutational disruptions in critical silk-associated genes including *FibH*, *FibL*, and *Ser1* adversely impair fibroin biosynthesis and silk gland functionality, while viral pathogens such as *Bombyx mori* nucleopolyhedrovirus (BmNPV) and densovirus (BmDNV) induce glandular degeneration and metabolic exhaustion. Furthermore, climatic extremities, elevated atmospheric humidity, pesticide residues, and nutritionally deficient mulberry foliage exacerbate larval physiological stress and neuro-endocrinal instability. Despite its deleterious economic implications, NSS possesses remarkable scientific significance as a model system for molecular genetics, recombinant protein expression, seribiotechnology, and functional genomic investigations. Integrated multidisciplinary interventions involving precision environmental regulation,

molecular breeding, disease surveillance, and climate-resilient sericultural technologies are indispensable for mitigating NSS and ensuring sustainable silk production under rapidly changing ecological paradigms.

Keywords: Non-Spinning Syndrome, Silkworm Physiology, Seribiotechnology, Cocoon Productivity, Environmental Stressor**s.**

Introduction

Sericulture, the exquisitely sophisticated science and art of natural silk production through the domestication and rearing of silkworms, has sustained agrarian civilizations for millennia and continues to constitute a pivotal component of rural bio-economies across Asia. In countries such as India, China, Japan, and Thailand, sericulture transcends its identity as a mere agro-industrial enterprise and remains profoundly interwoven with cultural heritage, ecological sustainability, women empowerment, and decentralized rural employment generation. The domesticated mulberry silkworm, *Bombyx mori* L., epitomizes one of humanity's most remarkable achievements in insect domestication, having co-evolved under anthropogenic selection pressure into an extraordinarily efficient biological producer of silk - nature's most lustrous and resilient proteinaceous fibre.

The economic edifice of sericulture is fundamentally predicated upon the silkworm's remarkable physiological capability to synthesize and extrude silk proteins in the form of a compact cocoon during the terminal larval stage. Under normal developmental conditions, silkworm larvae traverse five distinct instars while subsisting exclusively upon nutritionally enriched mulberry (*Morus* spp.) foliage. Upon attaining physiological maturity during the fifth instar, the larvae cease feeding, undergo profound endocrine and metabolic transformation, and initiate cocoon spinning behaviour — an intricate neurophysiological phenomenon regulated by endocrine signalling, silk gland maturation, and behavioural synchronization.

However, the sericultural landscape has recently witnessed the alarming emergence of a devastating physiological anomaly termed Non-Spinning Syndrome (NSS), wherein mature larvae fail to spin cocoons or produce malformed, flimsy, discontinuous, and commercially valueless silk masses. What was once regarded as an occasional pathological aberration has now evolved into an increasingly recurrent and economically catastrophic phenomenon across diverse sericultural ecosystems, thereby threatening the sustainability and profitability of global silk production systems (Venkatachalapathy *et al.,* 2004).

I. Biology and Physiology of Cocoon Spinning

Cocoon spinning in silkworms constitutes an extraordinarily complex physiological and behavioural process orchestrated through precise interactions among genetic determinants, hormonal cascades, silk gland physiology, and environmental stimuli. The paired silk glands — particularly the posterior silk gland (PSG) and middle silk gland (MSG) — undergo remarkable

hypertrophic enlargement during the terminal larval stages and synthesize vast quantities of fibroin and sericin proteins. Fibroin serves as the structural core of silk filaments, while sericin functions as a cementing glycoprotein binding fibroin strands together (Akai, 1979).

The transition from larva to pupa is hormonally governed by juvenile hormone (JH) and ecdysteroids, especially ecdysone, which regulate moulting, metamorphosis, silk secretion, and spinning behaviour. Any perturbation in these tightly regulated endocrine pathways may precipitate catastrophic physiological dysfunction culminating in non-spinning manifestations.

I. Etiological Determinants of Non-Spinning Syndrome

1. Genetic and Molecular Aberrations

Genetic instability constitutes one of the principal determinants underlying non-spinning syndrome. Mutations in critical silk-associated genes such as *FibH* (Fibroin Heavy Chain), *FibL* (Fibroin Light Chain), and *Ser1* profoundly impair fibroin biosynthesis and filament assembly. Furthermore, transcriptional regulators including *SGF1* and *POUM2* may undergo molecular disruptions, thereby inhibiting silk gland differentiation and protein secretion.

Certain mutant strains such as *csr* (cocoonless silkworm race), *ns* (non-sericin), and *fl* (flaccid larvae) exhibit heritable non-spinning phenotypes resulting from defective silk gland morphogenesis and endocrine dysregulation.

2. Viral and Pathogenic Invasions

Among infectious etiologies, *Bombyx mori* nucleopolyhedrovirus (BmNPV) and *Bombyx mori* densovirus (BmDNV) are particularly notorious for inducing profound cytopathological alterations within silk gland tissues. Viral replication results in glandular hypertrophy, epithelial necrosis, metabolic exhaustion, and suppression of fibroin synthesis.

Additionally, bacterial pathogens such as *Serratia marcescens* and fungal organisms including *Aspergillus* spp. induce toxemia, gut dysbiosis, and neurophysiological impairment, thereby disrupting cocoon spinning behaviour.

3. Climatic and Environmental Perturbations

Silkworm physiology is exquisitely sensitive to environmental fluctuations. Elevated temperatures exceeding 30°C accelerate larval metabolism and induce premature physiological senescence, thereby impairing silk gland maturation and spinning activity. Conversely, low temperatures retard endocrine synchronization and cocoon formation.

Excessive humidity during spinning stages induces abnormal diuresis, cocoon staining, and filament discontinuity, while low humidity desiccates silk secretions and prevents filament extrusion. Poor aeration, overcrowding, and abrupt photoperiodic disturbances further intensify physiological stress.

4. Nutritional Deficiencies and Mulberry Quality

The nutritional integrity of mulberry foliage profoundly influences silk protein biosynthesis. Leaves deficient in proteins, amino acids, minerals, and moisture adversely affect silk gland development during the critical fourth and fifth instars.

Mulberry cultivated under drought stress, salinity, nutrient depletion, or pesticide contamination produces nutritionally inferior foliage incapable of supporting optimal fibroin synthesis.

5. Toxicological Implications of Agrochemicals

Indiscriminate pesticide application represents one of the gravest anthropogenic threats to sericulture. Insect growth regulators (IGRs) such as pyriproxyfen, methoprene, and fenoxycarb maintain persistently elevated juvenile hormone levels, thereby disrupting metamorphosis and cocoon spinning.

Heavy metals including cadmium (Cd), lead (Pb), and zinc (Zn) bioaccumulated through industrial effluents or contaminated irrigation water induce oxidative stress, mitochondrial dysfunction, and degeneration of silk gland tissues.

II. Reasons for Non-Spinning in Silkworms

Non-spinning silkworms fail to produce proper commercial cocoons due to several biological, environmental, and managerial factors (Fehmi Gurel., 2025. The major reasons include :

1. Failure of Silk Secretion

Some silkworms are unable to secrete silk properly because of physiological or glandrelated abnormalities.

2. Poor Nutrition

Insufficient or low-quality mulberry leaves weaken larval growth and reduce spinning ability.

3. Unsuitable Temperature and Humidity

Extreme environmental conditions disturb normal larval metabolism and cocoon formation.

4. Disease Infection

Diseases such as grasserie, flacherie, muscardine, and pebrine adversely affect silk gland functioning and spinning behaviour.

5. Genetic or Hereditary Defects

Certain genetic abnormalities may result in defective silk production or spinning incapability.

6. Improper Rearing Management

Overcrowding, poor hygiene, delayed feeding, and inadequate ventilation create stress in larvae.

7. Chemical or Pesticide Exposure

Feeding contaminated leaves or exposure to toxic chemicals may damage silk glands and prevent spinning.

8. Weak or Diseased Larvae

Physically weak larvae often fail to complete normal cocoon formation.

9. Mounting Defects

Lack of suitable mountages or improper mounting practices can interrupt spinning activity.

10. Environmental Stress

III. Physiological and Economic Consequences

Non-spinning syndrome exerts profoundly deleterious consequences upon cocoon productivity, silk quality and sericultural profitability.

IV. Impact of Non-Spinning Silkworms on Sericulture

1. **Reduced Silk Production;** Non-spinning silkworms fail to secrete adequate fibroin and sericin proteins, resulting in poor or zero silk filament yield.
2. **Increased Economic Losses;** Unspun or defective cocoons are unsuitable for reeling and are often discarded, causing heavy post-rearing wastage.
3. **Decline in Farmer Income:** Poor cocoon quality and reduced market value directly affect the profitability and livelihood of sericulture farmers.
4. **Higher Rearing Expenditure:** Expenses incurred on mulberry feeding, labour, and maintenance become unproductive when larvae fail to spin cocoons.
5. **Genetic and Breeding Problems:** Hereditary non-spinning traits may s **V. Major manifestations include:**

- Complete failure of cocoon formation.
- Production of loose, flimsy, malformed, or discontinuous cocoons.
- Prolonged larval duration and impaired pupation.
- Elevated larval mortality and physiological exhaustion.
- Severe reduction in shell ratio, reelability, filament denier, and raw silk quality. Economically, NSS precipitates drastic declines in cocoon yield per 100 Disease Free Layings (DFLs), destabilizes farmer income, and compromises the competitiveness of national silk industries within global markets.

VI. Scientific Significance and Biotechnological Opportunities

Paradoxically, non-spinning silkworms have emerged as invaluable experimental models in contemporary seribiotechnology and molecular entomology (Sindhu *et al.,* 2024).

1. Recombinant Protein Production; Non-spinning strains are increasingly utilized as living bioreactors for producing:

- Human collagen
- Antimicrobial peptides
- Vaccines
- Industrial enzymes
- Therapeutic biomolecules

2. Gene Editing and Functional Genomics; Advanced genome editing technologies such as CRISPR-Cas9 facilitate targeted manipulation of silk genes, enabling elucidation of:

- Silk biosynthetic pathways
- Promoter activities
- Endocrine regulation
- Insect developmental physiology

3. Nutraceutical and Feed Applications: Non-spinning pupae rich in proteins, lipids, vitamins, and bioactive compounds possess substantial commercial potential as:

- Poultry feed supplements
- Aquaculture protein sources
- Functional food ingredients
- Nutraceutical formulations

VII. Integrated Preventive and Management Strategies (Kyung Hun Park *et al.,* 2007).

1. Environmental Regulation

- Maintain optimum temperature (24–28°C) and humidity (70–80%). Ensure proper ventilation and avoidance of overcrowding.

2. Nutritional Management

- Utilize nutritionally enriched and pesticide-free mulberry foliage.
- Apply balanced organic and inorganic nutrient management in mulberry gardens.

3. Disease Surveillance

- Strict hygienic disinfection of rearing houses.
- Early diagnosis and elimination of infected larvae.

4. Genetic Improvement

- Eliminate defective races through molecular screening.
- Develop stress-tolerant and disease-resistant silkworm hybrids.

5. Digital and Precision Sericulture

Emerging IoT and AI-driven technologies enable:

- Real-time environmental monitoring
- Early disease prediction
- Automated rearing advisories
- Precision mountage management

VIII. Future Perspectives for Managing Non-Spinning in Silkworms

1. Development of Climate-Resilient Silkworm Strains

Advanced breeding techniques such as genomics, CRISPR-Cas9 gene editing, and marker-assisted selection can help develop silkworm strains resistant to heat, diseases, and environmental stress.

2. Improvement of Silk Gland Efficiency

Selection of genotypes with stronger and healthier silk glands can reduce the incidence of non-spinning even under unfavorable environmental conditions.

3. Use of Transgenic and Gene-Edited Silkworms

Genetically improved silkworm lines can enhance larval survival, silk secretion, and cocoon productivity under climatic and nutritional stress.

4. Adoption of Seribiotechnology

Recombinant silk protein production using microbial or insect cell systems can provide alternative methods for silk production beyond conventional cocoon reeling.

5. Utilization of Non-Spinning Larvae as Value-Added Products

Non-spinning larvae and pupae can be utilized for producing protein-rich food supplements, animal feed, nutraceuticals, and bio-products.

6. Development of Silk-Based Biomaterials

Biotechnology can promote the use of silk proteins in medical sutures, cosmetics, tissue engineering, and drug delivery systems.

7. Integrated Sericulture Farming Models

Linking sericulture with pupal processing industries and by-product utilization can create additional income opportunities for farmers and reduce waste.

8. Implementation of Circular Economy Approaches

Both silk and silkworm by-products can be commercially utilized, ensuring sustainable and eco-friendly sericulture practices.

9. Digital Monitoring through IoT and Sensors

Sensors and smart devices can continuously monitor temperature, humidity, CO_2 levels, and larval health to maintain ideal rearing conditions.

10. Application of Artificial Intelligence (AI) in Sericulture

AI-based image analysis and machine learning tools can detect early disease symptoms, stress behavior, and non-spinning tendencies, enable timely interventions and improving cocoon productivity.

Conclusion

Non-spinning syndrome represents a formidable physiological, pathological, and economic challenge confronting modern sericulture. The disorder originates from a multifactorial interplay of genetic aberrations, pathogenic invasions, endocrine disturbances, environmental stressors, toxicological insults, and nutritional deficiencies that collectively compromise silk gland functionality and cocoon spinning behaviour. Nevertheless, the phenomenon also offers extraordinary scientific opportunities in molecular genetics, recombinant protein production, and seribiotechnology. Comprehensive multidisciplinary interventions integrating molecular

diagnostics, precision environmental management, genetic improvement, farmer-centric extension strategies, and sustainable biosecurity practices are indispensable for mitigating the menace and ensuring the long-term resilience of sericulture.

The future sustainability of global silk production ultimately depends upon humanity's capacity to decipher, manage, and innovatively harness the biological complexities underlying non-spinning syndrome in silkworms.

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References

1. Akai, H. (1979). Hormonal control of silk production in silkworm, *Bombyx mori*. *Japan Agricultural Research Quarterly, 13*(2), 116–122.
2. Gurel, F. (2025). Non-spinning syndrome in silkworm (*Bombyx mori* L.) rearing and its possible causes. *Turkish Journal of Agriculture, 13*(6), 1675–1685.
3. Park, K. H., Kim, B. S., Park, Y. K., & Lee, H.-D. (2007). Relationship between non-spinning syndrome of silkworm *Bombyx mori* and pesticide exposure. *Korean Journal of Pesticide Science, 11*(4), 238–245.
4. Sindhu, R., Sahana, G., Bhuvaneswari, E., Mallikarjuna, G., Satish, L., Moorthy, S. M., & Gandhi Doss, S. (2024). Identification and molecular analysis of proteins associated with non-spinning disease in the silkworm, *Bombyx mori*. *International Journal of Biochemistry Research & Review, 33*(6), 408–414.
5. Venkatachalapathy, M., Reddy, G. V., Manjula, A., & Kamble, C. K. (2004). Non-spinning in silkworms: Causative factors. *Indian Silk, 43*, 9–10.

CONSTRAINTS AND CHALLENGES HINDERING THE DEVELOPMENT OF SERICULTURE AND POST-COCOON TECHNOLOGY IN NORTH-EASTERN INDIA

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Abstract

Sericulture constitutes a vital agro-based rural industry possessing immense potential for employment generation, women empowerment, and sustainable livelihood development in Northern India. Despite favourable agro-climatic conditions and abundant human resources, the sericulture sector in this region remains comparatively underdeveloped when contrasted with the southern states of India. The present article critically examines the multifaceted constraints and developmental bottlenecks hindering the expansion of sericulture and post-cocoon technology in Northern India. Major challenges include climatic instability, inadequate availability of high-yielding mulberry varieties, technological backwardness in silkworm rearing, prevalence of silkworm diseases and pests, infrastructural deficiencies, weak extension services, and limited institutional support. Furthermore, the post-cocoon sector suffers from obsolete reeling technologies, poor cocoon quality, inadequate silk processing infrastructure, market volatility, and insufficient value-addition facilities. Socioeconomic vulnerabilities, labour shortages, fragmented landholdings, and inadequate region-specific research further exacerbate the stagnation of the industry. These cumulative constraints significantly affect cocoon productivity, silk quality, farmer profitability, and overall industrial competitiveness. The article emphasizes the necessity for a holistic and technologically integrated developmental approach encompassing scientific rearing practices, modernization of post-cocoon technologies, climate-resilient innovations, infrastructural strengthening, effective extension mechanisms, and policy-oriented institutional interventions. Sustainable advancement of sericulture in Northern India can

substantially contribute towards rural industrialization, economic diversification, and socio-economic upliftment of marginalized farming communities.

Keywords: Sericulture Constraints, Post-Cocoon Technology, Climatic Vulnerability, Technological Backwardness, Rural Livelihood Development.

Introduction

Sericulture, a highly specialized agro-based and labour-intensive rural industry associated with the cultivation of host plants, silkworm rearing, cocoon production, and silk processing, occupies a position of considerable socio-economic and cultural significance in India. Renowned globally for producing all commercially important varieties of natural silk, India possesses substantial ecological diversity favourable for sericultural expansion. Besides its economic contribution through employment generation and foreign exchange earnings, sericulture functions as an important instrument for rural industrialization, women empowerment, poverty alleviation, and sustainable livelihood security among marginalized farming communities. Owing to its low investment requirements and high employment potential, the sector has emerged as one of the most remunerative cottage-based agro-industries in the country.

Despite possessing favourable agro-climatic conditions and abundant human resources, Northern India has not achieved proportionate advancement in sericulture when compared with the southern states such as Karnataka, Andhra Pradesh, Tamil Nadu, and Telangana, where scientific and commercial sericulture has attained remarkable industrial development. States including Jammu & Kashmir, Himachal Pradesh, Uttarakhand, Uttar Pradesh, Bihar, Punjab, Haryana, and parts of NorthEastern India possess immense potential for mulberry, tasar, eri, and oak tasar silk production; nevertheless, the region continues to experience considerable developmental stagnation. The growth of sericulture in Northern India is severely constrained by climatic instability, poor mulberry productivity, inadequate silkworm disease management, technological backwardness, infrastructural deficiencies, weak extension systems, fragmented landholdings, and limited institutional support mechanisms (Basavaiah and Kallimani, 2021).

Furthermore, the post-cocoon sector in Northern India remains technologically underdeveloped and economically vulnerable due to obsolete reeling machinery, poor cocoon quality, inadequate silk processing infrastructure, lack of scientific grading systems, and unorganized marketing networks. The increasing impacts of climate change, rural labour migration, declining youth participation in agriculture, and competition from synthetic textile industries have further aggravated the challenges confronting the sericultural economy of the region. Therefore, comprehensive understanding of the multifactorial constraints affecting sericulture and post-cocoon technology in Northern India is indispensable for formulating sustainable developmental strategies aimed at technological modernization, productivity enhancement, value addition, and

long-term socio-economic revitalization of rural sericultural communities (Rekhamoni *et al.,* 2023)

The stagnation of sericulture in Northern India is not attributable to a singular factor but rather to a complex interplay of climatic adversities, technological inadequacies, socio-economic vulnerabilities, infrastructural deficiencies, and postcocoon processing constraints. These multifactorial impediments have considerably restricted productivity, cocoon quality, value addition, and market competitiveness.

1. Climatic Instability and Environmental Vulnerability

One of the foremost impediments affecting sericultural advancement in Northern India is climatic inconsistency and ecological unpredictability. Sericulture is an exceptionally climate-sensitive enterprise wherein even minor fluctuations in temperature, humidity, rainfall, and photoperiod significantly influence silkworm growth, cocoon formation, fecundity, and silk filament quality (Rajput., 2025).

Northern India frequently experiences:

- Severe winter stress
- Heat waves during summer
- Irregular rainfall patterns
- Prolonged droughts
- Heavy fog and frost incidence

Such climatic extremities adversely affect:

- Mulberry leaf quality
- Nutritional composition of foliage
- Silkworm metabolism
- Larval survivability
- Cocoon shell ratio

Moreover, climate change-induced ecological disturbances have intensified the incidence of pest outbreaks and pathogenic infections, thereby causing substantial crop losses and economic instability among sericulture farmers.

2. Scarcity of Quality Mulberry Planting Material

The absence of region-specific high-yielding and stress-tolerant mulberry varieties constitutes another serious developmental bottleneck. Most mulberry varieties cultivated in Northern India are either poorly adapted to low-temperature conditions or exhibit inadequate leaf productivity (Rajput., 2025).

Major problems include:

- Limited availability of certified saplings
- Poor nursery management

- Inadequate irrigation facilities
- Low adoption of improved mulberry varieties
- Soil nutrient depletion

Consequently, inferior leaf quality directly affects silkworm nutrition, leading to poor cocoon yield and reduced raw silk recovery.

3. Technological Backwardness in Silkworm Rearing

The majority of sericulture farmers in Northern India continue to practice traditional and unscientific rearing methodologies (Rajput., 2025). Modernized technologies relating to:

- Shoot rearing
- Environmental regulation
- Hygienic disinfection
- Bed cleaning
- Integrated pest management
- Chawki rearing remain inadequately disseminated among rural rearers.

Inadequate technical literacy and poor extension outreach further aggravate the problem. As a result:

- Larval mortality remains high
- Disease infestation becomes recurrent
- Cocoon uniformity deteriorates
- Productivity per disease-free laying remains unsatisfactory

4. Prevalence of Silkworm Diseases and Pest Infestation

Silkworms are highly susceptible to several pathogenic diseases such as:

- Pebrine
- Grasserie
- Flacherie
- Muscardine

Additionally, pest infestations by:

- Uzi fly
- Dermestid beetles
- Ants and predatory insects cause severe economic losses.

The absence of advanced diagnostic laboratories, poor availability of disinfectants, and inadequate farmer awareness regarding prophylactic measures substantially limit effective disease management. Disease outbreaks frequently culminate in crop failure, discouraging farmers from continuing sericulture as a sustainable livelihood enterprise.

5. Infrastructural Deficiencies and Financial Constraints

Sericulture development in Northern India is severely constrained by inadequate infrastructural facilities such as:

- Insufficient rearing houses
- Lack of grainage centres
- Poor transportation facilities
- Absence of irrigation systems
- Limited cold storage facilities
- Inadequate cocoon markets

Most sericulture farmers belong to economically weaker rural communities with limited access to institutional credit and agricultural insurance schemes. High initial investment requirements and delayed financial returns further discourage youth participation in sericulture activities.

6. Deficiencies in Extension Services and Skill Development

Extension education and farmer-oriented training programmes remain insufficient in many northern states. The lack of effective coordination among research institutions, extension agencies, and farming communities has resulted in minimal technological adoption (Rajput., 2025).

Critical issues include:

- Inadequate farmer training
- Weak field-level supervision
- Lack of demonstration units
- Poor awareness regarding scientific rearing practices
- Limited women-centric skill development programmes

This technological communication gap continues to impede the transformation of sericulture into a commercially viable enterprise.

Problems in Post-Cocoon Technology in Northern India (Choudhari *et al.,* 2024)

1. Obsolete Reeling and Spinning Technologies

Post-cocoon technology constitutes one of the weakest components of Northern Indian sericulture. Most reeling units still rely on conventional charkha and cottage basin systems characterized by:

- Low efficiency
- Poor silk recovery
- High yarn breakage
- Inferior filament uniformity

The absence of automatic and semi-automatic reeling machines considerably reduces international competitiveness of silk produced in the region.

2. Poor Cocoon Quality and Inadequate Grading Systems

Due to improper silkworm rearing practices and climatic stress, cocoon quality often remains inconsistent. Major quality issues include:

- Thin cocoon shell
- Uneven filament denier
- Stained cocoons
- Low reelability percentage

Furthermore, scientific cocoon grading and quality evaluation mechanisms remain poorly institutionalized, resulting in exploitation of farmers by middlemen and traders.

3. Lack of Modern Silk Processing Infrastructure Northern India suffers from inadequate:

- Reeling centres
- Twisting units
- Dyeing facilities
- Weaving clusters
- Silk testing laboratories

This infrastructural lacuna prevents value addition and compels farmers to sell raw cocoons at comparatively lower prices. The absence of integrated silk industrial clusters significantly hampers commercialization and employment generation.

5. Marketing Constraints and Price Fluctuation

The sericulture sector in Northern India is highly vulnerable to market instability and price volatility. Farmers frequently encounter:

- Exploitative intermediaries
- Unorganized marketing systems
- Lack of minimum support prices
- Delayed payments
- Limited export connectivity

Imported silk and synthetic textile substitutes further intensify market competition, adversely affecting profitability and sustainability.

6. Inadequate Research and Region-Specific Innovation

Although several research institutions are functioning in India, region-specific technological innovations for Northern Indian sericulture remain comparatively limited. Insufficient research on:

- Cold-tolerant silkworm breeds
- Climate-resilient mulberry varieties
- Disease-resistant hybrids

- Mechanized post-cocoon technologies has restricted productivity enhancement and industrial modernization.

7. Socio-Economic and Labour-Related Challenges

Migration of rural youth towards urban employment opportunities has generated acute labour scarcity in sericulture operations. Since sericulture is labourintensive and requires continuous supervision, declining rural workforce participation severely affects productivity.

Additional socio-economic challenges include:

- Fragmented landholdings
- Low literacy rates
- Gender inequalities
- Weak cooperative structures
- Limited entrepreneurial motivation

Some More Major Constraints Faced in Sericulture and Post-Cocoon Activities (Subhra Chanda *et al.,* 2014).

1. Lack of Timely Guidance: The majority of respondents (85.00%) reported lack of timely guidance as the most serious constraint, indicating inadequate technical support and extension services.

2. Lack of Improved Reeling and Spinning Machines: About 78.33% of respondents faced difficulties due to the non-availability of improved reeling and spinning machinery, which adversely affected yarn quality and productivity.

3. High Cost of Rearing Equipment and Production Technologies: Approximately 76.66% of respondents reported that expensive rearing equipment and sericulture technologies limited their capacity to adopt scientific practices.

4. Lack of Technical Guidance: Nearly 71.66% of respondents experienced inadequate technical guidance regarding cocoon processing and yarn production technologies.

5. Lack of Awareness on Technology Adoption: About 70.00% of respondents lacked awareness regarding modern sericultural technologies and scientific management practices.

6. Lack of Proper Incentives from Government and NGOs: Around 66.66% of respondents stated that insufficient financial incentives and institutional support hindered sericultural development.

7. Insufficient Training Facilities: Approximately 65.83% of respondents reported inadequate training opportunities related to rearing, reeling, spinning, and post-cocoon management.

8. High Labour Wages: About 64.16% of respondents identified increasing labour wages as a major socio-economic constraint affecting profitability.

9. Lack of Capital: Nearly 60.00% of respondents faced financial difficulties due to insufficient capital and limited access to institutional credit facilities.

10. Lack of Frequent Contact with Extension Personnel: More than half of the respondents (53.33%) experienced poor communication and inadequate interaction with extension officials and technical experts.

Strategies to Overcome Constraints in Sericulture and Post-Cocoon Technology in Northern India (Mrittika *et al.,* 2023)

1. Development of Climate-Resilient Varieties

Introduce drought, frost and disease-tolerant mulberry varieties and silkworm breeds suitable for Northern Indian climatic conditions.

2. Modernization of Rearing Technologies

Promote scientific silkworm rearing practices such as shoot rearing, environmental control systems, and hygienic rearing methods to improve cocoon productivity.

3. Strengthening Farmer Training Programmes

Conduct regular training, demonstrations, and awareness programmes to enhance technical knowledge among sericulture farmers.

4. Improvement of Post-Cocoon Infrastructure

Establish modern reeling, spinning, twisting, dyeing, and weaving units for better silk quality and value addition.

5. Scientific Disease and Pest Management

Implement integrated pest and disease management strategies along with regular monitoring and diagnostic facilities.

6. Expansion of Institutional Credit and Subsidies

Provide financial assistance, low-interest loans, subsidies, and crop insurance schemes to encourage sericulture adoption.

7. Development of Organized Marketing Systems

Establish regulated cocoon markets, digital trading platforms, and minimum support pricing systems to ensure fair returns to farmers.

8. Promotion of Research and Technological Innovation

Strengthen region-specific research on silkworm breeding, mulberry improvement, and mechanized post-cocoon technologies.

9. Encouragement of Women and Youth Participation

Promote entrepreneurship, self-help groups, and skill-development programmes to increase employment and rural participation.

10. Adoption of Sustainable and Eco-Friendly Practices

Encourage organic sericulture, biodiversity conservation, and environmentally sustainable silk production systems for long-term ecological stability.

Future Perspectives of Sericulture in Northern India

1. Development of Climate-Resilient Technologies

Introduction of climate-tolerant mulberry varieties and disease-resistant silkworm breeds suitable for fluctuating northern climatic conditions can significantly enhance cocoon productivity and silk quality.

2. Modernization of Post-Cocoon Technology

Adoption of advanced reeling, spinning, twisting, dyeing, and weaving technologies will improve raw silk recovery, filament quality, and international market competitiveness.

3. Strengthening of Research and Innovation Systems

Region-specific scientific research on silkworm breeding, pest and disease management, and sustainable sericultural practices can accelerate technological advancement and industrial growth.

4. Expansion of Farmer Training and Extension Services

Scientific capacity-building programmes, digital extension platforms, and field-level demonstrations can improve farmer awareness regarding modern sericultural practices.

5. Establishment of Integrated Silk Industrial Clusters

Development of integrated cocoon markets, reeling centres, silk processing units, and textile industries can promote value addition and rural industrialization.

6. Promotion of Women and Youth Participation

Encouraging women entrepreneurship and attracting rural youth towards scientific sericulture can strengthen labour availability and rural employment generation.

7. Enhancement of Institutional Credit and Market Support

Easy access to financial assistance, crop insurance, subsidies, and organized marketing systems can improve economic sustainability among sericulture farmers.

8. Adoption of Eco-Friendly and Organic Sericulture

Increasing global demand for biodegradable and eco-compatible silk products offers significant opportunities for promoting organic sericulture in Northern India.

9. Strengthening Disease and Pest Management Strategies

Scientific surveillance systems, diagnostic laboratories, and integrated pest management approaches can minimize crop losses and improve silkworm health.

10. Promotion of Public–Private Partnerships

Collaboration among government institutions, research organizations, private industries, and farmer cooperatives can accelerate commercialization and technological modernization of the sericulture sector.

11. Development of Export-Oriented Silk Enterprises

Improvement in silk quality, branding, packaging, and value addition can enhance export potential and global competitiveness of Northern Indian silk products.

12. Sustainable Rural Livelihood and Employment Generation

Sericulture possesses immense potential to emerge as a sustainable agro-based enterprise capable of generating continuous employment and improving socioeconomic conditions of rural communities.

Conclusion

Northern India possesses enormous yet insufficiently exploited potential for diversified sericultural advancement owing to its heterogeneous agro-climatic conditions, rich biodiversity, and abundant rural labour force. Nevertheless, the sector continues to remain economically fragile and technologically underdeveloped due to a multitude of interrelated constraints including climatic instability, ecological vulnerability, inadequate infrastructural facilities, poor access to institutional finance, technological backwardness, weak extension mechanisms, and underdeveloped postcocoon processing systems. These cumulative impediments have significantly restricted cocoon productivity, silk quality, farmer profitability, and industrial competitiveness, thereby preventing the region from attaining sustainable sericultural transformation and large-scale rural industrialization.

Therefore, the comprehensive revitalization of sericulture in Northern India necessitates a multidimensional and scientifically integrated developmental approach involving the introduction of climate-resilient mulberry varieties and disease-tolerant silkworm breeds, strengthening of farmer-oriented training and extension services, modernization of reeling and post-cocoon technologies, establishment of integrated silk industrial clusters, expansion of institutional credit and organized market support systems, promotion of scientific disease and pest management strategies, and enhancement of region-specific research and technological innovation. Unless these structural, technological, and institutional deficiencies are effectively addressed through coordinated policy interventions and scientific modernization, Northern India may continue to remain substantially lagging behind in realizing its full sericultural, economic, and rural developmental potential.

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References

1. Basavaiah, K., & Kallimani, C. S. (2021). Constraints faced in the adoption of technologies by chawki rearing centre entrepreneurs. *Journal of Extension Education, 32*(2), 6520–6530.
2. Choudhari, S. D., Perke, D. S., & Pathrikar, D. T. (2024). Garret ranking of constraints perceived by silkworm rearers in sericulture enterprise. *International Journal of Environment and Climate Change, 14*(1), 840–846.
3. Mrittika, S., Biswas, S., & Soumen, S. (2023). Factors and constraints involved in income generation from sericulture: A study in three districts of West Bengal, India. *Journal of Experimental Agriculture International, 45*(11), 219–228.
4. Rajput, Y. V. (2025). A conceptual review on sericulture in Northeast India: Viability, opportunities and policy pathways. *Archives of Current Research International, 4*(9), 65–89.
5. Rekhamoni, G., Gogoi, G., Saud, R. K., Bhuyan, N., Barthakur, A. K., Neog, M., & Pathak, P. K. (2023). A study on constraints of ericulture in Dhemaji district of Assam. *Indian Journal of Extension Education, 59*(1), 166–169.
6. Chanda, S., Mukhopadhyay, S. K., Saha, L. M., & Bindroo, B. B. (2014). Adoption behaviour of the sericulture farmers towards new technologies. *Uttar Pradesh Journal of Zoology, 34*(2), 79–85.

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PHYSIOLOGICAL DISORDERS IN CRUCIFEROUS CROPS: A COMPREHENSIVE REVIEW

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Abstract

Cruciferous crops belonging to the Brassicaceae, including cauliflower, broccoli, cabbage and Brussels sprouts, represent an important group of nutrient-rich vegetables cultivated worldwide. However, their productivity and market quality are frequently constrained by physiological disorders induced by abiotic factors such as nutrient imbalances, temperature extremes, moisture stress and suboptimal light conditions. These non-pathogenic disorders disrupt normal physiological processes, resulting in abnormalities such as buttoning, bolting, hollow stem and brown bud formation. Such disorders significantly reduce yield, visual quality and post-harvest shelf life. A comprehensive understanding of their underlying causes and effective management through balanced fertilization, regulated irrigation and environmental control is essential for improving crop performance and ensuring the sustainable production of high-quality cruciferous vegetables.

Keywords: Cruciferous Crops, Physiological Disorders, Abiotic Stress, Nutrient Imbalance, Crop Quality, Sustainable Production.

Introduction

Cruciferous or cole crops belonging to the family Brassicaceae constitute an important group of vegetable crops cultivated worldwide for their nutritional and economic value. These crops, particularly *Brassica oleracea* and its variants such as cauliflower, broccoli, cabbage and Brussels sprouts, exhibit remarkable morphological diversity, providing edible leaves, stems and inflorescences. They are rich sources of essential nutrients including vitamins A and C, minerals, carbohydrates and bioactive compounds such as glucosinolates, which are known for their health-promoting and anti-carcinogenic properties (Van Poppel *et al.,* 1999; Brown *et al.,* 2002). Among these, cauliflower (*Brassica oleracea* var. *botrytis*) is a highly valued cool-season vegetable cultivated for its compact edible curd, which ranges in colour from snow white to creamy yellow. It performs best under cool and moist climatic conditions, as both excessive heat and extremely low temperatures adversely affect curd development. Similarly, broccoli (*Brassica oleracea* var. *italica*) is increasingly popular due to its superior nutritional composition,

particularly its high content of glucosinolate derivatives. Cabbage and Brussels sprouts are also widely cultivated for their edible heads and buds, contributing significantly to human nutrition and dietary diversity. However, successful production of these crops largely depends on favourable environmental conditions, as they are highly sensitive to climatic fluctuations.

Despite their importance, cruciferous crops are frequently affected by various physiological disorders that significantly reduce yield, quality and marketability. Physiological disorders are non-pathogenic abnormalities caused by abiotic factors such as nutrient imbalances, temperature extremes, moisture stress, poor light intensity and soil-related constraints (Sharma, 2016). Unlike diseases caused by microorganisms, these disorders arise due to disturbances in normal plant metabolic and physiological processes. Although their symptoms often resemble those of pathogenic diseases, they cannot be controlled through plant protection measures and instead require proper management of environmental and nutritional conditions.

In cauliflower, adverse environmental conditions such as high temperature, moisture stress and improper nutrient supply can lead to disorders like buttoning, premature curd formation and bolting, resulting in poor quality produce (Rahman *et al.,* 2007; Singh *et al.,* 2019). Similarly, broccoli is prone to several abiotic disorders including brown bud, hollow stem, bracting and inflorescence deformities, which are often associated with temperature stress and nutrient imbalances, particularly involving nitrogen and calcium (Heather *et al.,* 1992; Maroto, 1997). Variations in water availability, solar radiation and mineral ratios such as potassium, calcium and magnesium also influence the incidence of these disorders. In general, the occurrence of physiological disorders in cole crops is closely linked to environmental stress conditions and mineral deficiencies, especially micronutrients. These disorders not only impair the visual quality of produce—such as colour, size, shape and texture-but also affect nutritional value, shelf life and consumer acceptability. Since market standards for fresh vegetables largely depend on their physical appearance and internal quality attributes, the presence of physiological disorders poses a serious challenge to sustainable production.

Therefore, understanding the causes, symptoms and management of physiological disorders in cruciferous crops is essential for improving crop performance, ensuring quality produce and enhancing economic returns. Effective management strategies involving balanced nutrition, proper irrigation, and suitable environmental control can play a crucial role in minimizing the incidence of these disorders.

Causes of Physiological Disorders in Cruciferous Crops

- **Temperature fluctuations:** Sudden variations in temperature, particularly extremes of heat or cold, disrupt normal plant growth and metabolic processes, leading to disorders such as bolting and blindness.

- **Nutrient imbalance or deficiency:** Inadequate or excess supply of essential nutrients (especially micronutrients like boron, calcium and molybdenum) is a major cause of physiological abnormalities affecting yield and quality.
- **Improper moisture availability:** Irregular water supply, including drought stress or excess moisture, affects nutrient uptake and plant development, resulting in disorders such as head splitting and tip burn.
- **Environmental stress conditions:** Factors such as poor light intensity, waterlogging and unfavourable climatic conditions interfere with physiological processes and induce abnormalities in plant growth.
- **Imbalanced cultural practices:** Improper irrigation, fertilization and crop management practices can aggravate physiological disorders by creating stress conditions in plants.

Physiological Disorders in Cauliflower

- **Riceyness:** It is a disorder observed during the curd development stage in cauliflower, where the normally compact curd becomes loose and granular due to elongation of flower pedicels. This results in the formation of numerous small, rice-like floral buds, giving the curd a coarse appearance. The disorder is mainly induced by fluctuations in temperature and the use of poor-quality seed stock (Grevsen *et al.,* 2003). It can be minimized through the selection of suitable cultivars, balanced nitrogen fertilization and cultivation of tolerant varieties.
- **Blindness:** In cauliflower refers to the absence of curd formation due to damage or failure of the terminal growing point at early growth stages. Affected plants exhibit thick, dark green, leathery leaves as a result of carbohydrate accumulation and remain in a vegetative state (Kalisza *et al.,* 2018). This condition is primarily caused by exposure to low temperatures and injury from pests such as cutworms. Preventive measures include protecting plants from low temperature stress and controlling insect damage through appropriate plant protection practices.
- **Buttoning:** It is characterized by the premature formation of small, undersized curds shortly after the development of a few leaves. This disorder arises due to several factors including nitrogen deficiency, transplantation of over-aged seedlings, delayed planting of early varieties and inadequate light conditions. Older seedlings often fail to establish sufficient vegetative growth prior to curd initiation, leading to reduced curd size (Wurr *et al.,* 1984). Proper nutrient management, timely transplanting of healthy seedlings and ensuring favourable growth conditions can effectively reduce its occurrence.
- **Pinking:** It is a physiological disorder in which cauliflower curds develop a pink or purplish discoloration due to exposure to high light intensity. This condition is associated

with the accumulation of anthocyanin pigments in the curd tissues. Maintaining proper curd coverage and minimizing direct light exposure can help prevent this disorder.

- **Black speck:** It is characterized by the appearance of small, dark lesions within the internal tissues of the curd, often accompanied by cellular breakdown. This disorder is commonly observed in late or snowball-type cultivars when exposed to elevated temperatures during curd development. Adoption of suitable cultivars and proper environmental management can help reduce its incidence.
- **Leafiness:** It is also referred to as bracting, is a physiological disorder characterized by the emergence of small green leaves between the segments of the curd, resulting in poor compactness and reduced market quality. This condition is primarily induced by elevated temperatures during the post-curd initiation stage and is often aggravated by delayed harvesting (Swati, 2015). High temperatures stimulate vegetative growth within the curd instead of proper floral development. The disorder can be minimized by selecting temperature-tolerant cultivars and ensuring timely harvesting to maintain curd compactness.
- **Multiple curds:** It is characterized by the development of several small, button-like curds arranged in clusters instead of a single compact head. This disorder occurs due to damage to the terminal bud or exposure to low temperatures, which induces lateral branching and formation of curds on secondary shoots (Olesen and Grevsen, 1993). Environmental stress and mechanical injury can also contribute to its occurrence. Preventive measures include protecting the growing point from damage and avoiding exposure to low temperature stress during early growth stages.
- **Browning:** It is a major physiological disorder caused by boron deficiency, often exacerbated by unfavourable soil conditions such as high pH, salinity or poor nutrient availability. It results in discoloration and deterioration of curd tissues, accompanied by a bitter taste. Initial symptoms include water-soaked patches on the curd and stem, which later turn brown or reddish-brown due to tissue breakdown (Vinod Kumar, 2012). In advanced stages, the stem becomes hollow and curd quality is severely affected. Boron deficiency may also impair root development and delay crop maturity, while phosphorus deficiency further reduces overall growth (Mitra, 1990). The disorder can be effectively managed through soil or foliar application of boron in the form of borax or boric acid, depending on soil conditions (Hazra and Som, 1999).
- **Whiptail:** It is a disorder caused by molybdenum deficiency, particularly in acidic soils where molybdenum availability is limited. It is characterized by chlorosis of leaf margins in young plants, followed by severe reduction in leaf blade development, leaving only the midrib intact (William Plant, 1951). The affected leaves appear strap-like and distorted,

ultimately affecting curd formation. Genetic variation among cultivars influences susceptibility to this disorder. Correction measures include application of sodium or ammonium molybdate and liming of acidic soils to improve nutrient availability (Scheffer *et al.,* 1987).

- **Hollow stem:** It is characterized by the splitting of the central fleshy portion of the stem, resulting in cavity formation that may extend throughout the stem. This disorder is mainly associated with excessive nitrogen fertilization, boron deficiency and rapid plant growth (Scaife *et al.,* 1990). Rapid expansion of internal tissues leads to breakdown of parenchyma cells, creating hollow spaces. It reduces structural strength and market value of the produce. The disorder can be minimized by maintaining balanced fertilization, adopting closer spacing and applying boron where necessary.
- **Fuzzy curd:** It is a condition in which the curd surface appears loose, velvety and less compact due to elongation of flower pedicels. This disorder may arise from genetic factors or unfavourable environmental conditions such as temperature fluctuations (Boersma *et al.,* 2013). It leads to reduced visual appeal and marketability. Proper selection of high-quality seeds, suitable varieties and adoption of recommended agronomic practices can help in reducing its occurrence.
- **Bolting:** It refers to premature flowering in cauliflower, which adversely affects curd formation and yield. Although cauliflower is a cool-season crop, prolonged exposure to low temperatures (below 10°C) followed by higher temperatures can induce early flowering. Other contributing factors include early sowing under warm conditions, sudden temperature fluctuations, poor nutrient supply, low seed viability and pest damage. Bolting results in loose, non-compact heads with reduced quality. It can be managed by selecting suitable cultivars, maintaining proper sowing time, ensuring balanced nutrition and protecting plants from environmental stress (Hadley and Pearson, 1998).
- **Tip burn:** It is a physiological disorder characterized by drying and necrosis of leaf margins, giving a papery appearance to affected tissues. It is mainly caused by localized calcium deficiency in rapidly growing tissues, even when soil calcium levels are adequate. Environmental factors such as high temperature, low or excessive soil moisture, and high relative humidity influence its incidence. Rapid growth induced by high nitrogen fertilization further aggravates the disorder (Jenkinson and Campbell, 1957). Tip burn is most common in young, actively growing leaves during curd development and can significantly reduce crop quality.

Physiological Disorders in Broccoli

- **Brown bud:** It is a common physiological disorder in broccoli characterized by brown discoloration of florets, leading to poor visual quality and reduced market acceptance. It is

primarily associated with exposure to high temperatures during the pre-harvest stage (Heather *et al.,* 1992) and is closely linked to calcium deficiency or impaired calcium translocation within plant tissues (Maroto, 1997). The disorder is more severe under rapid growth conditions where calcium demand exceeds supply. Imbalance in nutrient ratios, particularly higher potassium and magnesium levels relative to calcium, also contributes to its incidence.

- **Hollow stem:** It is characterized by the formation of cavities within the stem due to uneven and rapid enlargement of internal tissues. This disorder is mainly associated with excessive nitrogen fertilization, which promotes vigorous vegetative growth and is further influenced by irrigation practices that accelerate plant growth. Rapid cell expansion leads to breakdown of pith tissues, resulting in hollow spaces. The disorder is often more prominent in fast-growing cultivars and under favourable growth conditions that enhance biomass accumulation.
- **Bud deformation:** It refers to the abnormal development of broccoli heads, resulting in irregular shape, reduced compactness and poor uniformity. This disorder is mainly caused by temperature fluctuations, particularly high temperatures during curd initiation and development (Heather *et al.,* 1992). It is also influenced by nutrient imbalance and improper irrigation management, which disturb normal physiological processes. Environmental stress interferes with the differentiation and development of floral buds, leading to malformed heads.
- **Bracting:** It is a physiological disorder in which small leaf-like structures emerge between or around the broccoli florets, affecting head compactness and overall appearance. It is primarily induced by elevated temperatures during head formation (Maroto, 1997) and is further aggravated by moisture stress and nutrient imbalance (San Bautista *et al.,* 2005). High temperatures stimulate vegetative growth within the inflorescence, causing leaf formation instead of proper floral development. This results in reduced market quality due to loss of uniform structure and compactness.

Physiological Disorders of Cabbage

- **Blindness:** It is fundamentally a disorder of meristem dysfunction, where the apical meristem loses its capacity to differentiate into a compact head. This is closely linked to disruption in auxin–cytokinin balance, which regulates apical dominance and organ initiation. Low temperature stress, mechanical injury or insect damage alters hormonal signalling, leading to suppression of meristem activity. Additionally, impaired assimilate partitioning toward the growing point results in accumulation of carbohydrates in leaves, maintaining vegetative growth rather than head formation.

- **Bolting (Premature reproductive transition):** It is governed by vernalization-induced gene expression, where exposure to low temperatures activates flowering genes (such as *FLC* suppression in Brassicas). This triggers a shift from vegetative to reproductive growth. Once induced, subsequent warm temperatures accelerate gibberellin-mediated stem elongation and flowering (Verma, 2009). Bolting diverts photosynthates from head formation to reproductive structures, significantly reducing yield. The process is strongly influenced by genotype, photoperiod and thermal time accumulation.
- **Boron deficiency:** Boron is essential for cross-linking of pectic polysaccharides (RG-II) in cell walls, maintaining structural integrity. Deficiency disrupts cell wall formation, leading to cell separation, membrane leakage and oxidative damage (Norman, 1992). This results in water-soaked lesions that later become necrotic. Boron also plays a role in sugar transport and phenolic metabolism, and its deficiency leads to accumulation of toxic metabolites. Soil conditions such as high pH, drought or low organic matter reduce boron availability, intensifying the disorder.
- **Head splitting:** It results from excess internal turgor pressure caused by rapid water uptake following stress periods. The inner tissues expand faster than the outer epidermal layers, which have limited elasticity due to lignification and cuticle rigidity (Verma, 2009). This creates mechanical stress leading to rupture. Hormonal factors such as gibberellins and cytokinins promote rapid cell expansion, while excess nitrogen enhances growth rate, further increasing susceptibility.
- **Tip burn:** It is a classic example of calcium transport limitation rather than absolute deficiency. Calcium moves via the xylem and is dependent on transpiration; hence inner leaves with low transpiration receive inadequate calcium. This results in membrane destabilization, increased permeability and activation of cell wall-degrading enzymes, leading to necrosis. Reactive oxygen species (ROS) accumulation further accelerates cell death. Environmental conditions such as high humidity, rapid growth and excessive nitrogen exacerbate the disorder by reducing calcium distribution efficiency.
- **Black speck:** It is associated with oxidative stress and phenolic oxidation. Under stress conditions, phenolic compounds accumulate and are oxidized by polyphenol oxidase, forming dark pigments. Calcium deficiency and nutrient imbalance may destabilize cell membranes, enhancing oxidation processes. Cold storage can intensify symptoms due to altered respiration and metabolic activity, indicating its link to post-harvest physiology.
- **Black petiole:** This disorder is linked to ionic imbalance, particularly low potassium and high phosphorus levels, affecting osmotic regulation and enzyme activity. Potassium deficiency reduces turgor maintenance and disrupts carbohydrate translocation, while excess nitrogen promotes rapid growth, increasing metabolic demand (Becker and

Bjorkman, 1991). The resulting cellular collapse and pigment accumulation lead to blackening of petiole tissues.

- **Vein streaking necrosis & Necrotic spot:** These disorders are manifestations of localized programmed cell death (PCD) triggered by stress conditions. They involve disruption of vascular tissues, accumulation of toxic metabolites and oxidative damage. Post-harvest factors such as storage temperature and atmospheric composition influence their severity, indicating a strong connection with post-harvest physiology and metabolic imbalance.

Physiological Disorders of Brussels Sprouts

- **Blindness:** Unlike cabbage, Brussels sprouts depend on axillary bud development along the stem. Blindness occurs when hormonal regulation of lateral bud growth is disrupted, particularly due to imbalance between auxin (apical dominance) and cytokinin (lateral bud activation). Environmental stress or damage to the apical meristem interferes with this balance, leading to poor or uneven sprout formation.
- **Tip burn:** It is driven by restricted calcium movement to developing sprouts, especially under rapid growth conditions. Low transpiration rates within tightly packed sprouts limit calcium supply, leading to cell wall degradation, membrane leakage and necrosis (Guerena, 2006). Environmental stress and excessive nitrogen fertilization intensify the disorder by accelerating growth and increasing calcium demand.
- **Black speck:** In Brussels sprouts it is linked to metabolic stress and phenolic compound oxidation. Environmental factors such as temperature fluctuations and nutrient imbalance trigger oxidative reactions, resulting in dark pigmentation. The disorder often becomes more pronounced during storage due to changes in respiration and enzymatic activity.
- **Black petiole:** This disorder reflects nutrient imbalance affecting cellular metabolism, particularly involving potassium deficiency and phosphorus excess. These imbalances disrupt osmotic regulation and enzyme function, leading to tissue breakdown and discoloration. Rapid growth conditions further exacerbate the disorder.
- **Vein streaking necrosis:** This disorder involves damage to vascular tissues, likely due to stress-induced metabolic imbalance. It may be associated with impaired transport of water and nutrients, leading to localized necrosis along veins. Environmental stress and post-harvest conditions play a significant role in its development.

Conclusion

Physiological disorders in cruciferous (cole) crops are primarily influenced by complex interactions between environmental factors, nutrient availability and crop management practices. With the ongoing impacts of climate change, including rising temperatures, irregular rainfall patterns and increased frequency of extreme weather events, the incidence and severity of these disorders are expected to intensify. Since most cole crops are highly thermo-sensitive, even

minor deviations in temperature and moisture regimes can disrupt normal physiological processes, leading to significant yield and quality losses. Nutrient imbalances, particularly deficiencies of essential micronutrients such as boron, calcium and molybdenum, play a crucial role in the development of many physiological disorders. These deficiencies not only impair cellular functions such as cell wall formation and membrane stability but also affect metabolic activities and overall plant growth. Therefore, maintaining balanced fertilization through integrated nutrient management practices, including the use of organic manures and biofertilizers, is essential for sustaining soil health and reducing disorder incidence.

Effective management of physiological disorders requires a comprehensive approach that includes the selection of suitable cultivars adapted to specific agro-climatic conditions, timely transplanting, proper irrigation scheduling and careful regulation of nutrient supply. Farmers should be trained to accurately identify disorder symptoms and adopt location-specific management strategies. Additionally, improving soil conditions and ensuring consistent moisture availability can help minimize stress-induced abnormalities. Future research should focus on the development of climate-resilient and nutrient-efficient cultivars through breeding programs, along with advanced agronomic practices tailored to different agro-ecological zones. Strengthening research on genotype × environment interactions will further enhance the understanding of disorder occurrence. Such integrated efforts will not only improve crop productivity and quality but also support sustainable cultivation and expand export potential of Brassica crops in regional and global markets.

References

1. Becker, R., & Bjorkman, T. (1991). Cauliflower, broccoli and cabbage disorders in storage. *HortScience, 26*(5), 531–535.
2. Boersma, K., Drost, D., & Maughan, P. (2013). Causes and management of physiological disorders in cauliflower. *Horticultural Science Review, 45*(2), 89–95.
3. Brown, A. F., Yousef, G. G., Jeffery, E. H., Klein, B. P., Wallig, M. A., Kushad, M. M., & Juvik, J. A. (2002). Glucosinolate profiles in broccoli: Variation in levels and implications in breeding for cancer chemoprotection. *Journal of the American Society for Horticultural Science, 127*(5), 807–813.
4. Grevsen, K., Olesen, J. E., & Veierskov, B. (2003). Temperature effects on cauliflower curd development. *Scientia Horticulturae, 98*(1), 29–41.
5. Hadley, P., & Pearson, S. (1998). Effects of temperature and photoperiod on cauliflower development. *Journal of Horticultural Science & Biotechnology, 73*(1), 53–59.
6. Heather, D. W., Sieczka, J. B., & Dickson, M. H. (1992). Effects of temperature and cultivar on the incidence of brown bead in broccoli. *Journal of the American Society for Horticultural Science, 117*(3), 481–484.

7. Jenkinson, D. S., & Campbell, C. A. (1957). The influence of nitrogen fertilization on tip burn incidence. *Journal of Agricultural Science, 49*(2), 191–197.
8. Kalisza, A., Jezdinsky, A., & Kolota, E. (2018). Factors affecting cauliflower curd development and disorders. *Acta Horticulturae, 1227*, 123–130.
9. Maroto, J. V. (1997). *Horticultura herbacea especial*. Ediciones Mundi-Prensa.
10. Mitra, S. K. (1990). Nutritional disorders in vegetable crops. *Indian Journal of Horticulture, 47*(3), 345–352.
11. Norman, J. C. (1992). *Tropical vegetable crops*. Arthur H. Stockwell Ltd.
12. Olesen, J. E., & Grevsen, K. (1993). Temperature effects on curd initiation in cauliflower. *Journal of Horticultural Science, 68*(6), 965–971.
13. Rahman, M. M., Hossain, M. M., & Islam, M. S. (2007). Influence of environmental factors on growth and curd development of cauliflower. *International Journal of Sustainable Crop Production, 2*(6), 30–35.
14. San Bautista, A., Rueda, R., Pascual, B., Maroto, J. V., & Lopez-Galarza, S. (2005). Influence of substrates and nutrient solutions on broccoli disorders. *Acta Horticulturae, 697*(3), 275–277.
15. Scaife, A., Turner, M. K., & Morris, G. E. L. (1990). Effects of nitrogen and boron on hollow stem in cauliflower. *Annals of Applied Biology, 116*(2), 269–276.
16. Swati, S. (2015). Physiological disorders in cauliflower and their management. *International Journal of Applied Research, 1*(10), 456–460.
17. Sharma, R. R. (2016). *Physiological disorders of fruit and vegetable crops*. New India Publishing Agency.
18. Singh, B., Kumar, M., & Singh, R. (2019). Effect of environmental conditions and nutrient management on growth and yield of cauliflower. *Journal of Pharmacognosy and Phytochemistry, 8*(3), 1234–1238.
19. Van Poppel, G., Verhoeven, D. T. H., Verhagen, H., & Goldbohm, R. A. (1999). Brassica vegetables and cancer prevention: Epidemiology and mechanisms. *Advances in Experimental Medicine and Biology, 472*(2), 159–168.
20. Verma, L. R. (2009). *Postharvest technology of horticultural crops*. Indus Publishing Company.
21. William Plant, W. (1951). Molybdenum deficiency in cauliflower. *Nature, 167*(1), 123–124.

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DIVERSIFICATION OF LIVESTOCK IN PASCHIM MEDINIPUR DISTRICT OF WEST BENGAL: A MICRO-LEVEL STUDY

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Abstract

With a growing need to improve rural livelihood and agricultural sustainability, livestock diversification has become a significant priority in India. In the Paschim Medinipur district of West Bengal, the traditional farming system of livestock has shifted slowly from cattle-rearing to diversified farming practices, which include dairy, poultry, goat rearing and sheep rearing, piggery and duck rearing. The chapter scrutinizes the micro-level pattern, determinants and socio-economic implications of livestock diversification. The study gives an insight into the increasing reliance of small and marginal farmers on the diversity of their livestock enterprises in order to mitigate risks of crop failure, to gain farm income, to generate employment and in order to improve household nutrition acquisition. Although much progress has been made, Livestock development still faces constraints in the form of low availability of veterinary services, limiting production of feed, disease outbreaks, and marketing and distribution problems. The chapter ends with policy recommendations for Livestock Sustainable Diversification in the District.

1. Introduction

In India, agriculture is the main occupation of the majority of households in the villages. But due to high land pressures, reduction in profitability of crop cultivation, uncertainty of climate change, the farmers are forced towards alternative and additional sources of income generation. Livestock has become a major viable alternative for income diversification and risk abatement. The livestock sector in West Bengal is also a major source of agricultural gross value added (AGVA) and its importance extends beyond just providing employment to nutritional security, enhancing livelihoods and alleviating poverty. Paschim Medinipur district, with a well-diversified agro-climatic scenario and a major rural-oriented economy, can be considered to be appropriate to study the issues of diversification of livestock resources. Traditionally, in the District, farmers relied heavily on livestock, mainly for catering to the draught power needs and producing milk. The gradual economic reasons/prospective, market trends, technical developments and policy support have eventually spurred some farmers to diversify towards rearing of poultry, goats, pigs and other livestock. Livestock integration plays an important role in the rural economy of West Bengal nowadays, as it could give a steady source of income in light of the unpredictable nature of traditional crop-based agriculture. Livestock rearing plays a

vital role in creating livelihood and adding to the income, especially among smallholder farmers who are under economic pressure due to the land scarcity situation, particularly in Paschim Medinipur. This diversification is more and more necessary in order to avoid the weaknesses that land fragmentation and the volatility of agriculture related to climatic changes present. In addition, small-scale livestock keeping - such as cattle, goats, and poultry- fosters a risk management tool which helps families cope economically when environmental shocks affect harvests of the crops they grow. This multi-sectoral strategy also promotes equity in rural areas by distributing wealth more equitably than land-based assets, which are usually owned by larger agrarian households. Diversification of livestock is one of the important sources of income for the rural economy in Paschim Medinipur district, as it plays an important role in providing livelihood security, supplementing the income from farming and also helps households to mitigate risk.

2. Literature Review

Recent academic debates emphasize the shift from subsistence-based livestock rearing to diversified enterprise, with the capability to adapt to vulnerability due to climate uncertainties in both coastal and peripheral agro-ecological zones (Panja *et al.,* 2026). Such studies in similar areas, like the coastal salty lands of West Bengal, highlight the importance of these outbreaks in strengthening the economic resilience of farms in different situations of land holding (Ray & Dipyaman, 2016). Moreover, such use of non-conventional by-products in farming systems has demonstrated a synergetic and sensitized improvement in profitability and resource optimisation, which are key economic limitations in smallholder farm systems (Ahmed *et al.,* 2025). Amidst this, there is only partial research interest focused on specific livestock systems of Paschim Medinipur (Debasis *et al.,* 2018; Pattanayak & Naik, 2022) that fails to acknowledge the interaction between local infrastructure access and the sustainability of the livestock diversified systems. Filling these gaps requires a nuanced understanding of the dynamics between enterprise synergy and ecological reliability in the uptake of multi-species livestock systems for the local agrarian landscape (Kaur *et al.,* 2021). In particular, studies have shown that mixed farming systems, like dairy and goat operations, can have a considerable positive effect on the labor allocation and give marginalised farmers an important backup position in terms of income (Khan *et al.,* 2025). Such systems are very useful in buffering income shocks and smoothing consumption, as they are an intrinsic feature of crop failure (Jatav *et al.,* 2024; Kumar *et al.,* 2020). Furthermore, the integration of species with a shorter production cycle (Dumont *et al.,* 2020), such as poultry and related animals, allows more regular cash flows, thus reducing the effects of global market fluctuations on the financial stability of these households. Within this part of the country, there has been ample evidence in the Cape Fear region of how much can be

achieved to grow herd sizes drastically and boost annual household returns through science-based interventions via better breeding and health management (Datta, 2025).

3. Livestock Population in Sample Villages

Table 1 on the analysis of sample villages indicates clearly that rural households do not rely on a single kind of livestock, but they maintain a diversified combination of cattle, buffalo, goats and pigs. There is an apparent difference between the compositions of livestock across villages. Some villages have more cattle dominance and are more agricultural in terms of linkage, whereas those that had more goats or pigs, as the image of the dominance of small animals indicates small livestock as a source of additional income. The diversification is high in villages comprised of all four livestock types, which makes them less susceptible to crop failures and market volatility.

On the aggregate level, the overall livestock group of the sample villages is 1,169. Most of the various types of livestock are dominated by cattle with 38.32 percent, which underscores their biggest contribution towards the rural agrarian economy. Goats make up 29.43 percent of the total livestock as the second most vital category and they represent the increasing role of small ruminants in rural livelihoods. Buffaloes represent 17.96 percent, which implies their moderate proportion, which is mostly connected with the milk production. However, with the smallest proportion of 14.29 percent, pigs can be spread throughout all villages, which supports the idea that they are an additional source of income to some groups among the rural population. All in all, this distribution is that of a diversified and mixed livestock economy with large and small animals playing a role in ensuring livelihood security and economic resilience in the rural regions.

Villages with a heavy concentration of cattle: Eriamara (60.00%), Kushumdanga (58.73%), Palashi (50.00%) and Kundalpal (47.76%) are some villages with cattle that are heavily concentrated. This superiority suggests a close association with the agricultural industry, where cattle can be used in several ways, such as draught power, milk and manure. The high number of cattle in these villages is a symbol of the agrarian economy of the place and the fact that rural families still rely on cattle-related agricultural systems.

Villages dominated by goats: Goats form the highest percentage in such villages as Andhare (41.76%), Hajra (38.64%), Kalikakundu (41.07%), Palgere (38.57%) and Kharpara (43.55%). The fact that goats are the leading livestock also indicates the increased significance of rearing small livestock as a livelihood option, especially since it requires low capital, does not need a lot of space and can return on its investment very fast. The trend is particularly appropriate to marginal farmers and landless households, where goat rearing is an easy and stable source of additional income.

Buffalo population: Buffalo is found in the village of Hajra (27.27%), Kalikakundu (28.57%) and Bara (24.14) with relatively higher population. This fact has highlighted the significance of buffaloes in the production of milk, particularly in regions where sufficient food is readily available and water sources are reliable to sustain the species. The fact that buffalo inhabited these villages implies that they preferred to use higher milk production and market-oriented dairy practices.

Pig rearing villages: Pig population shows a significant proportion in such villages as Bara (27.59%), Kundalpal (23.88%) and Andhare (20.88%)(Table 1). The rearing of pigs in these villages is associated with certain socio-economic groups and is done as a low-cost livelihood activity. Because of its fast-breeding process and fast economic payoff, pig rearing is a significant source of additional income, especially to resource-deprived households.

Livestock diversification is an important component of the rural economy in Paschim Medinipur district, as it helps households reduce risk, supplement agricultural income and ensure livelihood security. The analysis of sample villages, as reflected in Table 1, clearly shows that rural households do not depend on a single type of livestock; instead, they maintain a diversified mix of cattle, buffalo, goats and pigs.

A clear variation in livestock composition is observed among villages. Some villages show cattle dominance, indicating stronger agricultural linkage, while others show a higher proportion of goats or pigs, suggesting dependence on small livestock as a supplementary income source. Villages with a mixed composition of all four livestock types demonstrate a high level of diversification, which reduces vulnerability to crop failure and market fluctuations.

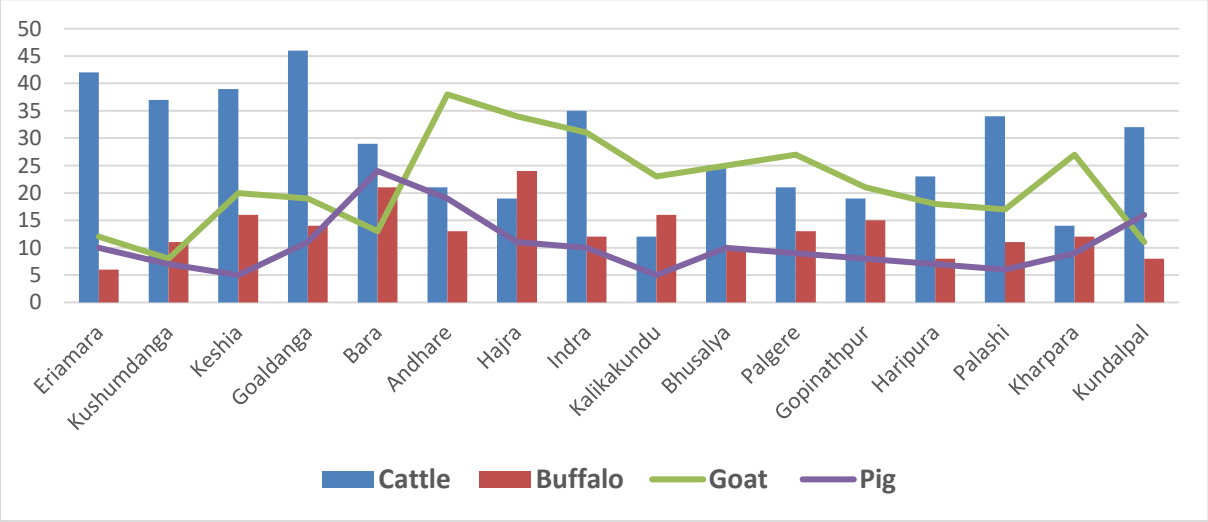

Figure 1: Livestock Population in Sample Villages

At the aggregate level, the total livestock population of the sample villages stands at 1,169. Among the different categories of livestock, cattle dominate with 38.32 percent, highlighting their primary role in supporting the rural agrarian economy. Goats constitute 29.43 percent of the total livestock, emerging as the second most important category and reflecting the growing

significance of small ruminants in rural livelihoods. Buffaloes account for 17.96 percent, indicating their moderate presence, mainly associated with milk production. Pigs, though forming the smallest share at 14.29 percent, are distributed across all villages, underscoring their role as a supplementary source of income for certain sections of the rural population. Overall, this distribution reflects a mixed and diversified livestock economy, where both large and small animals collectively contribute to livelihood security and economic resilience in rural areas.

Table 1: Village-Wise Total Livestock Population and Percentage Share

Villages	**Cattle**		**Buffalo**		**Goat**		**Pig**		**Total**	
Villages	**No.**	**%**	**No.**	**%**	**No.**	**%**	**No.**	**%**	**No.**	**%**
Eriamara	42	60.00	6	8.57	12	17.14	10	14.29	70	100
Kushumdanga	37	58.73	11	17.46	8	12.70	7	11.11	63	100
Keshia	39	48.75	16	20.00	20	25.00	5	6.25	80	100
Goaldanga	46	51.11	14	15.56	19	21.11	11	12.22	90	100
Bara	29	33.33	21	24.14	13	14.94	24	27.59	87	100
Andhare	21	23.08	13	14.29	38	41.76	19	20.88	91	100
Hajra	19	21.59	24	27.27	34	38.64	11	12.50	88	100
Indra	35	39.77	12	13.64	31	35.23	10	11.36	88	100
Kalikakundu	12	21.43	16	28.57	23	41.07	5	8.93	56	100
Bhusalya	25	35.71	10	14.29	25	35.71	10	14.29	70	100
Palgere	21	30.00	13	18.57	27	38.57	9	12.86	70	100
Gopinathpur	19	30.16	15	23.81	21	33.33	8	12.70	63	100
Haripura	23	41.07	8	14.29	18	32.14	7	12.50	56	100
Palashi	34	50.00	11	16.18	17	25.00	6	8.82	68	100
Kharpara	14	22.58	12	19.35	27	43.55	9	14.52	62	100
Kundalpal	32	47.76	8	11.94	11	16.42	16	23.88	67	100
Overall	448	38.32	210	17.96	344	29.43	167	14.29	1169	100

Source: Field Level Survey

4. Milk production in 16 sample villages in six months, 2020-21

Table 2 shows the production of milk (in liters) in 16 sample villages in 2020-21 according to the source of milk cattle, buffalo and goat. In each village, the amount of milk produced as well as the percentage of the total milk production is presented, leading to the amount of milk produced by a given village. A general aggregate is given at the bottom to emphasize the general trends of production.

General Trends in Milk Production

The total six-month milk output in all sample villages is 47,338 liters, signifying that livestock plays a significant role in the rural economy. A source-based analysis demonstrates that the majority of the production (47.51) is buffalo milk, closely trailed by cattle milk (44.86), with the relatively low proportion of goat milk (7.63) production. Conversely, goat rearing is an auxiliary activity, especially for small and marginal households, as it brings extra revenue and food supply. It is also possible to assume a diversified livestock structure based on the balanced participation of cattle and buffalo milk, which will minimize the production risk and provide a higher level of stability in the general milk production.

Cattle Milk

The cattle milk forms a significant portion of total milk production in various sample villages since rearing cows is a common practice in the study area. A significant reliance on cattle milk is observed in such villages as Eriamara (72.15%) and Kundalpal (60.94%), which means that the cattle population is relatively larger and cows are preferred to other livestock. This has been due to factors like less initial investment, simplicity in management, consistent milk production and ability to integrate cattle husbandry and crop farming systems. All in all, it can be concluded that cattle milk continues to play a role in the dairy activities in rural areas, as it adds 21235 liters over six months. Besides contributing to the household income, cattle rearing is also important in creating nutritional security and livelihood stability, especially in the case of small and marginal farmers. The same tendencies have been followed in rural India, where cattle milk constitutes a significant portion of overall milk production because of its availability and cost-effectiveness (NSSO, 2019; FAO, 2020).

Buffalo Milk

Buffalo milk comes out as the key positive influence on the overall production of milk in the sample villages, so it is the main producer of the rural dairy economy. The production of buffalo milk is more dominant in villages like Hajra (67.15%), Kalikakundu (67.89%) and Bara (59.81) (Table-2) and suggests the greater concentration of buffalo rearing and increased dependence on the buffalo-based dairying systems. The buffalo milk is mostly prevalent due to its fat and solid-not-fat, hence giving the farmers a better market price than the cattle milk. In addition, buffaloes are usually well adapted to local agro/ climatic conditions, especially in areas where there is an adequate water supply and fodder. Their capability to use course fodder effectively and their relatively higher milk production build on their economic viability. Buffalo rearing is therefore essential in promoting market-based dairy production, household earnings and livelihoods of the rural population (FAO, 2018; NDDB, 2020).

Table 2: Milk Production by Sample Villages during six months, 2020-21

Villages	Cattle-Milk		Buffalo-Milk		Goat -Milk		Total Milk	
Villages	Quantity		Quantity		Quantity		Quantity	
	Lit.	%	Lit.	%	Lit.	%	Lit.	%
Eriamara	1991	72.15	643	23.29	126	4.57	2759	100
Kushumdanga	1754	58.15	1178	39.06	84	2.79	3016	100
Keshia	1849	49.01	1714	45.43	210	5.57	3772	100
Goaldanga	2180	56.21	1499	38.65	200	5.14	3879	100
Bara	1375	36.56	2249	59.81	137	3.63	3760	100
Andhare	995	35.72	1392	49.96	399	14.32	2787	100
Hajra	901	23.53	2570	67.15	357	9.33	3828	100
Indra	1659	50.74	1285	39.31	326	9.96	3270	100
Kalikakundu	569	22.54	1714	67.89	242	9.57	2524	100
Bhusalya	1185	47.05	1071	42.53	263	10.42	2519	100
Palgere	995	37.26	1392	52.12	284	10.61	2671	100
Gopinathpur	901	33.02	1607	58.90	221	8.08	2728	100
Haripura	1090	51.04	857	40.11	189	8.85	2136	100
Palashi	1612	54.30	1178	39.69	179	6.01	2968	100
Kharpara	664	29.73	1285	57.57	284	12.70	2232	100
Kundalpal	1517	60.94	857	34.42	116	4.64	2489	100
Overall	21235	44.86	22491	47.51	3612	7.63	47338	100

Source: Field Level Survey

Goat Milk

Goat milk has a comparatively smaller but significant contribution to the total production of milk among the sample villages, which is based on the role of supplementation in the rural livestock economy. Such villages as Andhare (14.32%), Kharpara (12.70%) and Palgere (10.61) (Table 2) have relatively high percentages of goat milk production, which means that a larger percentage of their farming is based on small ruminants.

Even though goat milk production is not very large in quantity relative to that of cattle and buffalo milk, it is very significant in the nutritional security and livelihood support of small and marginal farmers and the landless population. Goat farming does not need much capital to start, has low feed requirements and does not demand complex management schemes, hence fitting well in the resource-poor setting. Also, the milk of goats is treasured due to its high digestive characteristics and nutritional value, which adds to its significance in the food of the countryside. Goat rearing, therefore, is a beneficial tool to diversify the income and minimize the risk in the rural environment (FAO, 2019; Kumar *et al.,* 2021).

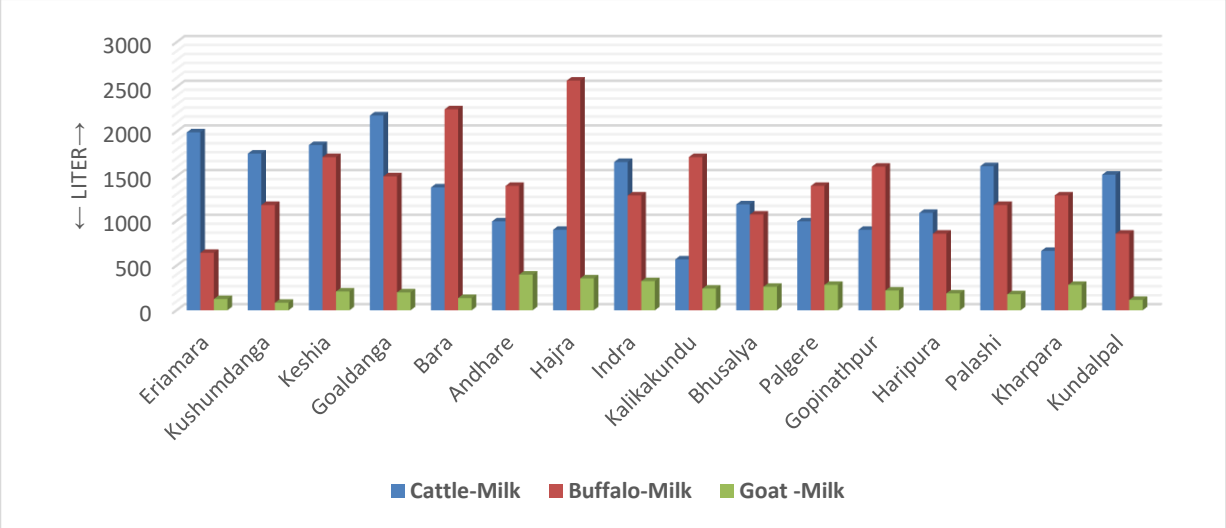

Figure 2: Cattle, Buffalo & Goat-Milk Production by Sample Villages

5. Egg, Fish and Meat Production by Sample Villages (2020–21)

Table 3 presents village-wise data on the production of eggs (in numbers), fish (in kilograms) and meat (in kilograms) for the sample villages during six months in 2020-21. These components represent important sources of animal protein, supplementary income and livelihood diversification in the rural economy of the study area.

Egg Production

Egg production across the sample villages exhibits moderate inter-village variation, ranging from 465 eggs in Indra to 972 eggs in Goaldanga, with an overall average of 801 eggs during the reference period. Villages such as Goaldanga (972), Kushumdanga (942), Bara (867) and Kharpara (869) record relatively higher levels of egg production, indicating a greater adoption of backyard poultry farming and wider household participation in poultry rearing activities.

Higher egg output in these villages may also be associated with better access to poultry inputs, such as chicks and feed, improved management practices and lower disease incidence. Backyard poultry in these areas appears to play an important role not only in meeting household nutritional requirements but also in generating supplementary income through periodic sale of eggs in local markets (Kondombo, 2005; Singh *et al.,* 2014).

In contrast, villages such as Indra (465) and Haripura (683) report comparatively lower egg production. This may be attributed to smaller poultry stock, limited household participation, higher mortality due to disease outbreaks and inadequate veterinary and extension services. Previous studies have shown that poor access to animal health services and a lack of technical knowledge significantly constrain poultry productivity in rural areas.

Despite these differences, egg production remains fairly evenly distributed across villages, suggesting that small-scale poultry farming is a widely practiced and accessible activity in the study area. Its low capital requirement, minimal land dependence and quick returns make it

particularly suitable for marginal and small farmers, women and landless households. As documented in the literature, backyard poultry contributes significantly to income diversification, nutritional improvement and livelihood resilience in rural economies (Ahuja *et al.,* 2008; Singh *et al.,* 2014).

Fish Production (Inland)

Fish production across the sample villages shows substantial inter-village variation, reflecting significant differences in access to water resources, aquaculture infrastructure and management practices. The lowest level of fish production is recorded in Eriamara (1,145 kg), while the highest is observed in Palgere (2,641 kg). Other villages with notably high fish output include Kundalpal (2,537 kg), Gopinathpur (2,398 kg) and Bhusalya (2,345 kg) (Table 3 & Fig. 3). The overall average fish production during the reference period is 1,881 kg, indicating that fisheries constitute an important but unevenly distributed livelihood activity in the study area.

Villages reporting higher fish production are likely to benefit from larger pond areas, better water retention capacity and more favourable agro-ecological conditions, along with a greater adoption of scientific Pisciculture practices. Previous studies have shown that access to perennial water bodies, quality fish seed and regular pond management significantly enhance fish productivity in rural areas (Jana and Mitra, 2016; Das *et al.,* 2018). In such villages, fish farming not only contributes to household consumption but also serves as a commercial activity generating supplementary income.

In contrast, villages with lower fish production may face several structural and institutional constraints, including limited pond ownership, seasonal drying of water bodies, poor water quality and inadequate access to extension services and technical knowledge. These limitations restrict the adoption of improved aquaculture technologies and reduce overall output. Studies by Sahoo *et al.* (2017) and Birthal *et al.* (2019) highlight that lack of institutional support, credit constraints and vulnerability to climatic variability are major impediments to fish production in smallholder systems.

The wide variation in fish production across villages suggests that fisheries are highly location-specific and more dependent on natural endowments and infrastructural support than activities such as poultry rearing. This underscores the need for village-specific interventions, including pond renovation, improved water management, timely supply of quality fingerlings and strengthened extension services, to enhance fish production and reduce inter-village disparities. Given its potential for income generation and nutritional security, promoting sustainable aquaculture could play a key role in diversifying rural livelihoods in the study area.

Meat Production

Meat production across the sample villages shows considerable variation, reflecting differences in livestock ownership, management practices and market orientation. Production levels range

from 493 kg in Kundalpal to 843 kg in Hajra, with an overall average of 729 kg during the reference period. Villages such as Hajra (843 kg), Haripura (831 kg), Bara (818 kg) and Bhusalya (813 kg)(Table 3 & Fig.3)) record relatively higher meat production, indicating a stronger prevalence of livestock rearing activities, particularly small ruminants such as goats and poultry birds raised for meat. Similar patterns have been documented in rural livestock systems, where small ruminants and backyard poultry form the backbone of meat production (Birthal & Negi, 2012; Kumar *et al.,* 2018).

The increased meat production in these villages can be explained by the increased livestock density, access to more resources of feed and the increased engagement of households in small-scale animal husbandry. The rearing of livestock is also a source of daily income and an asset accumulation tool to the rural household, especially to marginal and small farmers (Birthal *et al.,* 2015).

On the contrary, the villages like Kundalpal (493 kg) and Goaldanga (652 kg) have relatively reduced production of meat. This can be because of smaller herd sizes, availability of fodder and grazing land, cost of inputs, or household preferences on selling live animals instead of slaughtering them locally. According to the previous literature, livestock are sometimes held as a means of savings or insurance in numerous rural regions, thus restricting local meat production despite the animals within the region (Ellis, 2000; Kumar *et al.,* 2018).

Comprehensively, it is observed that meat production seems to be less dispersed than egg production because it is more capital-intensive and time-consuming, yet less dispersed than fish production, which is highly reliant on natural resource endowments. These findings indicate the need to improve the availability of fodder, veterinary services and the market infrastructure to increase the level of meat production and consolidate it in the diversification of livelihoods and nutritional security of rural people.

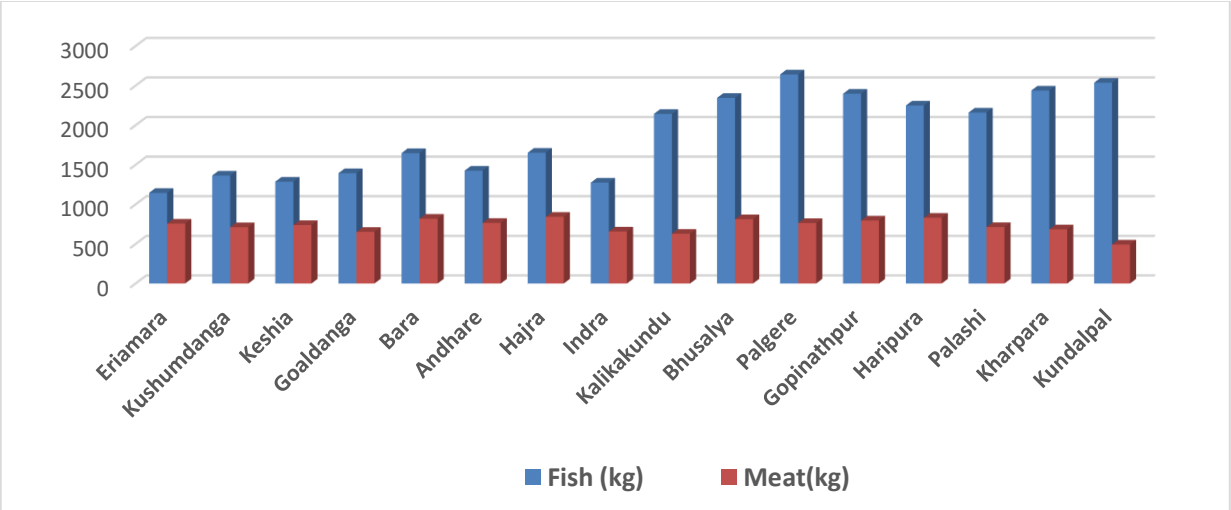

Figure 3: Fish and Meat Production by Sample Villages during six months, 2020-21

Table 3: Egg, Fish and Meat Production by Sample Villages during six months, 2020-21

Villages	Egg (numbers)	Fish (kg)	Meat (kg)
Eriamara	854	1145	756
Kushumdanga	942	1364	712
Keshia	846	1287	738
Goaldanga	972	1394	652
Bara	867	1647	818
Andhare	843	1425	765
Hajra	810	1652	843
Indra	465	1275	657
Kalikakundu	756	2143	629
Bhusalya	694	2345	813
Palgere	846	2641	764
Gopinathpur	834	2398	796
Haripura	683	2248	831
Palashi	764	2159	713
Kharpara	869	2438	684
Kundalpal	763	2537	493
Overall	801	1881	729

Source: Field Level Survey

6. Determinants of Livestock Diversification in Paschim Medinipur

There is a set of economic, social, institutional and environmental factors that affect livestock diversification in Paschim Medinipur. One of the most important factors of these is farm size. Small and marginal farmers, who account for the majority of agricultural households in the district, commonly also undertake diversified livelihoods such as poultry, goat rearing, Duck farming and piggery, which require lesser land, lower capital investment and sources of quick returns as compared to large-scale dairy farming. Larger farms, on the other hand, tend to have more financial and physical facilities, allowing them to be able to keep a superior quality herd and more modern systems of dairy management. Other critical constraints affecting diversification are access to institutional credit. Loans from commercial banks, cooperative societies, self-help groups (SHGs) and the microfinance institutions are available to the farmers, which allows them to invest in livestock sheds, improved breeds, feed, medicines and other inputs.

Farmers who have greater access to financial resources are more likely to engage in diversified enterprises of livestock and use modern production technologies. On the other hand, credit

access is an important constraint to investment and does not permit livestock activities to expand when credit is limited. Patterns of livestock diversification are also influenced by market access. Urban farmers are more likely to commercialize their dairy and poultry farming, as they are closer to the urban market, milk collection centres and transport facilities, thus guaranteeing demand and price realization. Demand for agricultural produce such as milk, eggs, meat, etc., from neighboring towns and cities has motivated rural families to expand their livelihoods. The establishment of efficient market linkages decreases the transaction costs and improves profit, so that the farmers are more motivated to engage in livestock-based enterprises. Access to and quality of veterinary healthcare services play a significant role in choices around livestock diversity. Increased access to veterinary hospitals, artificial insemination centres, vaccination services, disease diagnosis centres, extension services etc., will lead to better animal health and productivity. Regular veterinary care increases the suitability of farmers to invest in high-yielding breeds and commercial livestock activities. On the other hand, lack of technical support and regular outbreaks of diseases act as a brake on diversification and raise risks in production. Likewise, knowledge and awareness among farmers is also a major criteria. Farmers who are educated more easily adopt new technology, new scientific feeding practices, new breed development programs, and disease management practices. The knowledge of farmers is improved and diversified livestock enterprises are promoted through training programs, demonstration, exposure visits and extension activities organized by the government and university agriculture departments and non-governmental organizations (NGOs). Modern livestock management techniques have become even more evident through the use of mobile phones, social media and digital platforms, further enhancing awareness. Government policies and institutional support have become one of the driving forces of livestock diversification in the district. The Government of India and the Government of West Bengal have various schemes in place for providing subsidies, financial assistance, insurance, improvement of livestock and farmer training to livestock farmers. Dairy development, backyard poultry farming, goat keeping and women SHG are all playing a significant role in increasing livestock diversification. The institutional interventions have worked especially well to dismantle barriers and improve opportunities for the poorer households. Household income, family labor supply, family occupation and participation of women are also some of the socio-economic factors that determine diversification decisions. Livestock enterprises can be a vital source of additional income for land-starved farmers. Labor, particularly in the form of womens and elderly people, is available in the families which helps in running the activities of livestock owners. Livestock diversification is an effective opportunity to enhance women's livelihood and economic empowerment, given the key role women play in feeding, cleaning, milking and managing farming animals with respect to health. Another key factor is resource availability, such as feed

and fodder resources. Households with access to crop residues and common property resources, including areas for fodder cultivation and grazing lands, can keep more and diversified livestock, as can households with access to residues. The integration of crop farming and animal husbandry promotes the efficient use of resources, such as using agricultural by-products as feed for livestock and vice versa, and using livestock manure for crop fertilisation as an organic manure. In the past few years, environmental/climatic factors have become more important. The district is often subject to climatic uncertainty with frequent episodes of irregular rains, potential losses of rain causing drought-like conditions, and variability in agricultural productivity. These uncertainties make crop-based agriculture more susceptible and make livestock enterprises attractive to households as a risk-management strategy. Livestock enterprises are a relatively consistent source of income and serve as insurance against crop failures and market fluctuations. Lastly, consumer preferences and increasing demand for livestock food products hastened livestock diversification. The rising demand for milk and eggs, meat and processed animal products is in response to both growing urbanization (and associated population growth), and to rising incomes and nutrition consciousness. The growing market has helped to generate economic opportunities for rural households and to engage them in commercial livestock production, which has helped to diversify their livelihood portfolios. Therefore, Livestock diversification in Paschim Medinipur is influenced by farm characteristics, institutional supports, market availability, availability of resources, and environmental factors. All of these factors influence farmers' choices and the level and pathways of diversification of livestock farming systems.

Prbit Estimates of Household Participation

We first present the theoretical framework of the estimation of household participation in livestock rearing, followed by the empirical results. (HPLR) are made based on the theoretical background. A probit model was developed to examine the relationship between socio-economic characteristics and the level of participation of households in Livestock rearing. The demographic variables included in the empirical model are given in Table 4. The dependent variable is whether or not the household participates in livestock rearing in the Sabang block.

The other dependent variable is whether or not the household participates in livestock rearing (HPLR) in the Sabang block. The household demographic variables are Number of female workers per household (X_1), Per capita land (X_2), nearby open ground availability (X_3) and Per capita income(X_4).

$$HPLR = b_0 + b_1X_1 + b_2X_2 + b_3X_3 + b_4X_4 + b_5X_5 + U$$

The availability of nearby open ground may influence an individual’s level of participation in livestock rearing. The availability of nearby open ground is a dummy variable. It takes on the value of 1 if the household enjoys open ground facilities and 0 if not. At the household level, we

analyze the factors of household participation in livestock rearing (HPLR) like Number of female workers per household (X_1), Per capita land (X_2), nearby open ground availability (X_3), Per capita income(X_4) and Bank Loan(X_5)

Table 4: Probit Estimates of Household Participation in Livestock Rearing, (HPLR)

Variable	Coefficient	t-value/z-value	p>lzl	
Intercept	11.27	2.81**	0.001	Pearson Goodness of fit Chi-square = 67.02
NFW	2.521	1.99*	0.042	
PCL	-0.201	-2.32**	0.005	No. of observation= 60 P= 0.000
PCI	-0.027	-2.84**	0.008	R^2 = 0.77
OGA	1.360	1.63	0.241	
BL	1.481	1.79*	0.043	

Notes: NFW = Number of female workers per household, PCL = Per capita land, PCI = Per capita income, OGA = Nearby open ground availability (If Yes =1, No= 0) , BL = Bank Loan

** and * indicate coefficients significant at 1% and 5% level

Conclusion

In the Paschim Medinipur district, livestock diversification is an important part of the livelihood of the rural people. Adopting new practices, like traditional to diversified livestock farming, especially in dairies, poultry, goatries, duckery etc., has significantly boosted income generation, employment creation, nutritional security and poverty alleviation. The sector has tremendous potential in inclusive rural development, especially for the small and marginal farmers. The small and marginal farmers, who contribute the greater bulk of the entire agricultural households in the district, engage in poultry farming, goat rearing, duck farming and piggery due to comparatively less land and low initial investment and quick return as compared to large farm dairy operations. Conversely, larger farmers are likely to have higher financial and material capital and would be able to run a dairy business with improved breeds and management practices. Availability of institutional credit is another key determinant that affects diversification. Access to commercial banks, cooperative societies, Self-help Groups (SHG) and Microfinance institutions (MFI) resources facilitates farmers to invest in livestock sheds and improved livestock, feeds, medicines etc. Financial resources are a common factor that helps in the uptake of diversified livestock enterprises and modern livestock production technologies by households. On the other hand, credit availability is limited, thus impeding investment and the growth of livestock operations. Market accessibility is also playing a key role in determining the livestock diversification trend. The farmers who live close to urban areas, markets, milk collection bases and transport agencies are more likely to do commercial dairy and poultry farming because of guaranteed markets and remuneration. Milk, eggs, meat and other livestock products are required each day by other towns and cities in the vicinity, which propelled the rural

households to diversify their production system. Good market linkage can lessen the transaction costs and augment farmers' profit, which makes an incentive for them to engage in livestock-based enterprises. Nonetheless, important obstacles must be overcome in veterinary services, feed availability, marketing infrastructure and financial access in order to achieve this potential. Overall, a comprehensive policy framework that prioritizes productivity improvement, market linkages, and sustainable resource management would further reinforce the importance of livestock diversification in driving rural prosperity in Paschim Medinipur.

Policy Recommendations

Veterinary healthcare infrastructure needs to be strengthened by providing proper veterinary services in farms and establishing mobile veterinary services and routine vaccination programmes in Paschim Medinipur for sustainable livestock diversification. Fodder production and feed management need to be encouraged to ensure sufficient quality feed and fodder are available. Institutional credit and livestock insurance, as well as government support schemes, ought to be increased to stimulate investment in diversified livestock businesses. To increase farmers' income and access to the markets, efficient marketing infrastructure like milk collection centres, livestock markets, storage and transport networks should be developed. Producer cooperatives, Farmer-Producer Organizations (FPOs) and Self-Help Groups (SHGs) should be promoted to secure more power in collective bargaining and to face minimum market constraints. There is a need for regular training and extension services for the dissemination of scientific livestock management and support for value addition and processing activities will provide opportunities for further employment and income. Moreover, women should be highlighted, breed upgrading, and resilient in times of climate change. Livestock farming should also be given special consideration for sustaining this development and to achieve inclusive rural development.

Reference

1. Ahmad, R., Kumar, P., & Paul, T. (2026). Role of livestock interventions in enhancing goat and backyard poultry farming among rural farmers of Bankura, West Bengal. *International Journal of Agriculture Extension and Social Development*, *9*, 42–45. https://doi.org/10.33545/26180723.2026.v9.i3sa.3413
2. Ahmed, S., ALAM, M., & Huda, F. A. (2025). Profitability and Multi-functionality of Integrated Enterprise Model Cattle Farming in Coastal Region of Bangladesh: A Socio-Economic Analysis. *Research in Agriculture, Livestock and Fisheries*, *12*(2), 161–173. https://doi.org/10.3329/ralf.v12i2.83440
3. Benoît, M., Martin, G., Steinmetz, L., Ulukan, D., Bernes, G., Brock, C., Foye, A. de L., Grillot, M., Magne, M.-A., Meischner, T., Moerman, M., Monteiro, L., Oehen, B., Parsons, D., Primi, R., Schanz, L., Winckler, C., & Dumont, B. (2023). Interactions between animal

enterprises and marketing strategies shape organic multispecies farming systems. *Agronomy for Sustainable Development*, *43*(6). https://doi.org/10.1007/s13593-023-00930-8

4. Bhattacharjee, S., & Dhara, K. C. (2023). Socio-Economic Characteristics, Adoption, and Knowledge Level of Goat Farmers: A Study in Aspirational Districts of West Bengal, India. In *IntechOpen eBooks*. IntechOpen. https://doi.org/10.5772/intechopen.1001299
5. Bhattacharjee, S., Dhara, K. C., Kesh, S. S., Ghosh, S., Dasgupta, P., Giri, A. K., Sarkar, B., Roy, S., Bose, S. P., & Dey, A. R. (2021). Study on Socio-Economic Status and Constraints Faced by the Livestock Farmers of the Aspirational Districts of West Bengal, India. *International Journal of Research and Innovation in Social Science*, *5*(7), 331–340. https://doi.org/10.47772/ijriss.2021.5714
6. Biswas, T., Kamal, M., Sani, J., Shahid, T., Tabassum, F. T., Hossain, F., & Roy, S. (2024). Income Diversification of Rural Households in Bangladesh (2022-23). *International Journal of Innovative Science and Research Technology (IJISRT)*, 2414–2418. https://doi.org/10.38124/ijisrt/ijisrt24jun1500
7. Datta[5], Dr. K. C. D., Dr. Shyam Sundar Kesh[2], Dr. Uttam Roy[3], Dr. Paramita Dasgupta[4], Mr. Biman Sarkar[4], Mr. Suprava Roy[4], Ms. Shrestha Roy[4], Ms. Disha Banerjee[4], Ms. Aditi. (2025). Transforming Rural Livelihoods: Women Entrepreneurs Driving Scientific Livestock Farming. *Zenodo (CERN European Organization for Nuclear Research)*. https://doi.org/10.5281/zenodo.18005523
8. Debasis, M., Kumarjit, M., & Lakshmikanta, D. (2018). Trend, pattern and determinants of crop diversification of small holders in West Bengal: A district-wise panel data analysis. *Journal of Development and Agricultural Economics*, *10*(4), 110–119. https://doi.org/10.5897/jdae2018.0921
9. Dumont, B., Puillet, L., Martin, G., Savietto, D., Aubin, J., Ingrand, S., Niderkorn, V., Steinmetz, L., & Thomas, M. (2020). Incorporating Diversity Into Animal Production Systems Can Increase Their Performance and Strengthen Their Resilience. *Frontiers in Sustainable Food Systems*, *4*. https://doi.org/10.3389/fsufs.2020.00109
10. Islam, Md. M., Roy, K., Goswami, R., Rahman, M. C., Βέγυμ, Μστ. E. A., Mallick, S., Chowdhury, A., Mainuddin, M., & Monjardino, M. (2025). Farm diversification in the salt-affected coastal region of the Ganges Delta: Drivers and pathways to smallholder resilience. *Environmental and Sustainability Indicators*, *28*, 100997–100997. https://doi.org/10.1016/j.indic.2025.100997
11. Jatav, S. S., Naik, K., & Nayak, S. (2024). Assessing adaptive capacity to climate change of farmers in Gangetic Plains region, India. *Discover Agriculture*, *2*(1). https://doi.org/10.1007/s44279-024-00112-4

12. Jojo, N. S., & Prakash, J. (2018). Different Farm Production System Practiced in Simdega District, Jharkhand. *International Journal of Current Microbiology and Applied Sciences*, *7*(4), 2121–2128. https://doi.org/10.20546/ijcmas.2018.704.242
13. Kaur, J., Prusty, A. K., Ravisankar, N., Panwar, A. S., Shamim, M., Walia, S. S., Chatterjee, S., Pasha, Md. L., Babu, S., Jat, M. L., López-Ridaura, S., Groot, J. C. J., Toorop, R. A., Barba-Escoto, L., NOOPUR, K., & Kashyap, P. (2021). Farm typology for planning targeted farming systems interventions for smallholders in Indo-Gangetic Plains of India. *Scientific Reports*, *11*(1). https://doi.org/10.1038/s41598-021-00372-w
14. Khan, N., Rehman, A., & Rahaman, M. (2025). Socio-Economic Behaviour of Goat Husbandry in Aligarh District, U.P. *Economics World*, *12*(3). https://doi.org/10.17265/2328-7144/2025.03.002
15. Kumar, S., Mishra, A. K., Pramanik, S., Mamidanna, S., & Whitbread, A. (2020). Climate risk, vulnerability and resilience: Supporting livelihood of smallholders in semiarid India. *Land Use Policy*, *97*, 104729–104729. https://doi.org/10.1016/j.landusepol.2020.104729
16. Maity, S., Sahoo, S., & Govind, A. (2025). A field-based data-driven modeling approach for livelihood vulnerability examination of rice farmers considering climate risk in parts of West Bengal, Eastern India. *Discover Sustainability*, *6*(1). https://doi.org/10.1007/s43621-025-01711-x
17. Martin, G., Barth, K., Blanc, M., Dumont, B., Hübner, S., Magne, M.-A., Mosnier, C., Primi, R., Schanz, L., Werne, S., & Winckler, C. (2019). Diversified farming systems for improved sustainability of agriculture: potentialities and challenges. *Organic Eprints (International Centre for Research in Organic Food Systems, and Research Institute of Organic Agriculture)*.
18. Panja, A., Garai, S., Maiti, S., Choudhary, B. B., Zade, S. B., Veldandi, A., & Sankhala, G. (2026). Exploring determinants of climate change adaptation by smallholder livestock farmers in coastal West Bengal, India, using a double hurdle econometric approach. *Scientific Reports*, *16*(1), 2946–2946. https://doi.org/10.1038/s41598-025-32890-2
19. Patnaik, N. M., Pandey, D., Das, U., Acharya, P., & GEETA, G. (2025). Balancing livestock production and environmental sustainability: insights from the Indian context. *Current Science*, *129*(7), 601–606. https://doi.org/10.18520/cs/v129/i7/601-606
20. Pattanayak, U., & Naik, K. (2022). Assessment of Pattern and Sustainability of Livestock Diversification in Odisha. *Annals of Arid Zone*, *60*, 141-147. https://doi.org/10.56093/aaz.v60i3-4.131570

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