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AGRICULTURAL EXTENSION AND TECHNOLOGY ADOPTION IN INDIA: IMPLICATIONS FOR CROP PRODUCTIVITY, FARM ECONOMICS AND SUSTAINABLE AGRICULTURE: A REVIEW

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ABSTRACT

Agricultural extension plays a critical role in connecting agricultural research with farmers and facilitating the adoption of improved technologies in India. However, technology adoption remains uneven across crops, regions and farmer groups, contributing to persistent technology, extension and productivity gaps. This review synthesizes literature on agricultural extension and technology adoption in India, with emphasis on frontline demonstrations, on-farm testing, farmer training, participatory approaches and digital advisory services. A structured literature search using Scopus, Web of Science, Google Scholar and Science Direct was conducted to examine the evolution of extension systems, determinants of technology adoption, extension mechanisms, crop and pest-management technologies, adoption constraints, and emerging digital and artificial intelligence-enabled approaches. The review indicates that technical knowledge, economic feasibility, perceived risk, access to inputs and services, institutional support and technology-specific characteristics strongly influence adoption decisions. Locally relevant demonstrations, continuous technical guidance and farmer-centred extension can improve technology adoption, crop productivity and economic returns. However, high investment costs, inadequate infrastructure, limited technical capacity, digital inequalities and weak institutional coordination continue to constrain adoption, particularly among small and resource-constrained farmers. Strengthening research–extension–farmer linkages through integrated human and digital advisory systems, participatory approaches, capacity building, public–private partnerships and supportive policies is essential for improving technology adoption, farm profitability and sustainable crop production in India.

Key words: Agricultural Extension; Technology Adoption; Crop Productivity; Farm Economics; Frontline Demonstration; Climate-smart agriculture; Sustainable agriculture

Introduction

Agriculture remains central to India's food security, rural employment and livelihoods, while the productivity and sustainability of crop production increasingly depend on the effective dissemination and adoption of improved

agricultural technologies. Indian agricultural research has generated a wide range of technologies, including improved crop varieties, nutrient and weed management practices, pest and disease management, mechanization, precision agriculture and climate-smart production

practices. However, the development of a technically effective technology does not necessarily ensure its adoption under diverse farm-level conditions. A persistent gap often exists between technologies developed or validated through research and their actual use by farmers, contributing to technology, extension and productivity gaps across Indian agriculture (Varshney *et al.*, 2022; Ambawatia, 2020; Kurbah *et al.*, 2025).

Agricultural extension plays a critical role in bridging this research–farmer gap by connecting scientific knowledge with farmers’ production decisions. In India, extension has evolved from relatively centralized approaches to a pluralistic system involving State Departments of Agriculture, Krishi Vigyan Kendras (KVKs), Agricultural Technology Management Agency (ATMA), State Agricultural Universities, private organizations, farmer groups and digital advisory platforms. KVKs have contributed to research–extension–farmer linkages through on-farm testing, frontline demonstrations (FLDs) and farmer training, while ATMA promoted more decentralized and participatory approaches to technology dissemination (Subba & Mukhopadhyay, 2019; Varshney *et al.*, 2022). The increasing participation of private and digital actors has further expanded the reach of extension, although it has also created challenges related to coordination, accessibility and quality of advisory services (Pandey *et al.*, 2025).

Technology adoption is a complex behavioural and economic process rather than a simple consequence of information availability. Farmers’ decisions are influenced by expected profitability and risk, access to credit and inputs, farm and household characteristics, extension contact, social networks and institutional support. Technology-specific attributes such as relative advantage, compatibility, complexity, trialability and observability also influence adoption behaviour (Dissanayake *et al.*, 2022; Karbo *et al.*, 2024). Extension interventions such as FLDs, on-farm testing, farmer training, participatory approaches and ICT-based advisory services can facilitate adoption by reducing uncertainty, improving technical knowledge, demonstrating economic benefits and strengthening farmers’ confidence in new practices.

The importance of effective extension is particularly pronounced in India because farmers differ widely in landholding size, resource availability, education, irrigation access, market connectivity and digital literacy. Consequently, the adoption of improved varieties, nutrient and weed management, pest management, mechanization and climate-smart technologies remains uneven across regions and farmer groups. Small and marginal farmers,

women farmers and socially disadvantaged communities may face additional technical, economic and institutional barriers. At the same time, digital advisory services and emerging artificial-intelligence-enabled tools provide opportunities to complement conventional extension with more timely and scalable information delivery (Cerjak *et al.*, 2025; Li *et al.*, 2022).

Although considerable research has examined agricultural technologies, extension interventions and farmer adoption, evidence remains dispersed across crops, regions and technological domains. A synthesis is therefore needed to understand how extension contributes to technology adoption, how adoption affects crop productivity and economic outcomes, and what technical, economic, social, institutional and policy constraints continue to limit wider adoption. Such a perspective is particularly relevant for crop and pest-management technologies, where correct knowledge, timely application and continued technical support can influence both productivity and profitability.

Accordingly, this review examines the evolution and current structure of agricultural extension in India, the major theoretical foundations of technology adoption and the mechanisms through which extension facilitates technology transfer. It further reviews the adoption of major agricultural technologies, with emphasis on their implications for crop production, farm economics and pest-management practices, identifies the principal constraints affecting adoption, and discusses strategies involving strengthened extension capacity, digital and AI-enabled advisory, participatory approaches, public–private partnerships and supportive policies to improve the research–extension–farmer linkage.

Review Methodology

A structured literature search was conducted using Scopus, Web of Science, Google Scholar and Science Direct. The search used combinations of keywords including *agricultural extension*, *technology adoption*, *technology transfer*, *frontline demonstration*, *farmer training*, *digital extension*, *farm economics*, *integrated pest management*, *crop production* and *smallholder farmers*, along with relevant crop- and India-specific terms. Peer-reviewed research articles, review papers, meta-analyses and selected institutional publications were considered based on their relevance to agricultural extension, technology adoption, crop productivity, economic outcomes and pest-management practices. Indian studies were given greater emphasis, while selected international studies were included to provide broader conceptual and comparative perspectives. The retrieved

literature was synthesized thematically under agricultural extension systems, technology-adoption theories, extension mechanisms, major agricultural technologies, adoption constraints, production and economic outcomes, pest management, and emerging digital and AI-enabled extension approaches.

Agricultural Extension in India

Evolution of Extension Services:

Agricultural extension in India has evolved from centralized, technology-transfer approaches towards more participatory and location-specific systems. The Training and Visit (T&V) system promoted regular contact between extension personnel and farmers, but its standardized and largely top-down approach was less suited to the diverse conditions of Indian agriculture (Feder *et al.*, 1987; Rokvic & Vaško, 2016). The establishment of Krishi Vigyan Kendras (KVKs) from 1974 strengthened research–extension–farmer linkages through on-farm testing, frontline demonstrations (FLDs) and farmer training. Evidence indicates that KVK interventions can improve farmers' knowledge, skills and adoption of improved technologies, including spillover benefits beyond direct participants (Varshney *et al.*, 2022). The Agricultural Technology Management Agency (ATMA) further promoted decentralized and demand-driven extension approaches (Subba & Mukhopadhyay, 2019). Evidence from India also indicates that ATMA interventions can contribute to improved farmer knowledge, skills and adoption behaviour (Subba & Mukhopadhyay, 2019).

Public, Private and Pluralistic Extension Systems:

India now has a pluralistic extension system involving State Departments of Agriculture, KVKs, State Agricultural Universities, ATMA, private agribusinesses, non-governmental organizations, farmer organizations and digital advisory providers. Public institutions provide broad institutional coverage, while private and farmer-based organizations can offer specialized, market-oriented and demand-responsive services (Pandey *et al.*, 2025). Evidence from ATMA-linked interventions also indicates the importance of institutional extension support in improving farmers' knowledge, diversification and economic outcomes (Jangde *et al.*, 2024). Public–private partnerships can further support technology transfer by combining technical knowledge, training and market linkages, although effective coordination and clear institutional responsibilities are important (Aseete *et al.*, 2023).

Digitalization has expanded this pluralistic system through mobile advisory services, digital platforms and other ICT-based tools. These approaches can improve

the timeliness and scale of information delivery, but unequal access to devices and connectivity, limited digital literacy and the need for reliable and locally relevant information remain important concerns (Kishore Kumar *et al.*, 2026). Thus, digital extension should complement rather than replace conventional extension services.

Current Challenges:

Despite institutional expansion, agricultural extension in India continues to face inadequate staffing, limited infrastructure and finance, uneven coverage of farmer training and FLDs, and coordination challenges among different extension providers (Nagar *et al.*, 2021). Evidence from KVKs also indicates constraints related to training and institutional capacity (Yadav *et al.*, 2020). Unequal access to digital technologies, limited digital literacy, language diversity and farmer trust can further restrict inclusive extension delivery (Cerjak *et al.*, 2025; Kishore Kumar *et al.*, 2026). Strengthening human resources, institutional coordination, participatory approaches and digital capacity is therefore important for making extension more responsive to farmers' diverse needs. The major extension approaches operating in India, their institutional actors, mechanisms and contribution to technology dissemination are summarized in Table 1.

Technology Adoption in Agriculture

Concept of Technology Adoption:

Technology adoption in agriculture is the process through which farmers become aware of, evaluate, try and incorporate a new technology or practice into their farming systems. Adoption is influenced not only by access to information but also by perceived benefits, compatibility with existing practices, cost, risk and the farmer's ability to implement the technology (Dissanayake *et al.*, 2022; Karbo *et al.*, 2024).

Adoption can occur through individual experience as well as social interaction, extension contact and farmer-to-farmer learning. Demonstrations, training, field days and exposure visits allow farmers to observe technologies under practical conditions and can accelerate their wider diffusion. Evidence from India shows that frontline demonstrations and capacity-building programmes can improve technology adoption and generate spillover effects through farmer networks (Varshney *et al.*, 2022).

Factors Influencing Technology Adoption:

Farmers' adoption decisions are shaped by personal, farm, economic, social, institutional and technology-specific factors. Education and farming experience influence understanding, while farm size, labour, irrigation, input availability and access to credit affect the feasibility

Table 1: Major agricultural extension approaches in India and their contribution to technology adoption.

Extension approach	Major institutional actors	Main mechanism	Contribution to technology adoption	Major limitation
Training and Visit (T&V)	State extension departments	Regular agent–farmer contact	Dissemination of standardized recommendations	Relatively top-down and costly
Krishi Vigyan Kendra (KVK)	ICAR, KVKs, SAUs	On-farm testing, FLDs, training	Local validation and demonstration of technologies	Limited staff and coverage
Agricultural Technology Management Agency (ATMA)	District and state agencies	Participatory and demand-driven extension	Farmer-oriented technology planning and dissemination	Uneven implementation
Private extension	Agribusiness and input companies	Input-linked advisory and technical support	Timely and specialized information	Commercial orientation
NGO/FPO-based extension	NGOs, FPOs, farmer organizations	Group-based learning and advisory	Collective learning and market linkage	Variable institutional capacity
Digital extension	Mobile platforms, ICT services, digital providers	Apps, SMS, call centres and online advisory	Rapid and scalable information delivery	Digital divide, literacy and trust
Public–private partnerships	Government and private/NGO actors	Technology transfer, training & market linkage	Wider reach & integrated service delivery	Governance and accountability

of adoption. Expected profitability, investment requirements and production risk also strongly influence decisions (Dissanayake *et al.*, 2022; Karbo *et al.*, 2024). Extension contact, farmer groups and social networks can reduce uncertainty and support experiential learning. Technology characteristics such as relative advantage, compatibility, complexity, trialability and observability also influence adoption behaviour (Rogers, 1988; Karbo *et al.*, 2024). Evidence from India further shows that frontline demonstrations, training and on-farm learning can strengthen adoption by providing practical evidence of technological benefits (Madhushekar *et al.*, 2021; Varshney *et al.*, 2022).

Major Theories of Technology Adoption:

The Diffusion of Innovations (DOI) theory is one of the most widely used frameworks for understanding agricultural technology adoption. It views diffusion as a social process influenced by communication channels, time and the perceived characteristics of an innovation (Rogers, 1988). Economic approaches emphasize profitability, risk, resource availability and expected returns, whereas behavioural approaches such as the Technology Acceptance Model (TAM) and Theory of Planned Behaviour (TPB) emphasize perceived usefulness, ease of use, attitudes and social influences.

A systematic review of theories used to understand farmer technology adoption in low- and middle-income countries found that diffusion- and utility-based approaches remain prominent, while emphasizing the need

for context-specific frameworks incorporating institutional and socio-economic conditions (Karbo *et al.*, 2024). Accordingly, technology adoption in India can be understood as the outcome of interactions among technology characteristics, farmer resources, economic incentives, extension support and social learning. Technology adoption should also be assessed beyond the proportion of farmers using a technology. Changes in yield, profitability, livelihood outcomes, horizontal diffusion and technology or extension gaps provide broader evidence of whether research recommendations have translated into meaningful farm-level outcomes (Madhushekar *et al.*, 2021; Madhushekar *et al.*, 2022b; Narendar *et al.*, 2023b). The major determinants influencing farmers' decisions to adopt agricultural technologies and their implications for crop production and farm economics are summarized in Table 2.

Role of Agricultural Extension in Technology Adoption

Frontline Demonstrations (FLDs):

Frontline demonstrations (FLDs) provide a practical link between research recommendations and farmers by demonstrating technologies under actual field conditions. Comparing recommended practices with farmers' existing practices helps reduce uncertainty and allows farmers to assess productivity, profitability and management requirements before adoption (Varshney *et al.*, 2022; Ambawatia, 2020).

Table 2: Major determinants of agricultural technology adoption and their implications for crop production and farm economics.

Determinant	Examples	Influence on adoption	Implication for crop production/economics	Illustrative evidence
Farmer characteristics	Age, education, experience	Affects understanding and evaluation	Influences capacity to implement technologies	Dissanayake <i>et al.</i> , (2022)
Farm resources	Farm size, irrigation, labour	Determines feasibility of adoption	Influences input and machinery use	Tanti <i>et al.</i> , (2023)
Economic factors	Cost, profitability, credit, risk	Strongly affects adoption decisions	Determines returns and investment feasibility	Van Loon <i>et al.</i> , (2020); Narendar <i>et al.</i> , (2023a), Madhushekar <i>et al.</i> , (2022b)
Extension access	FLDs, OFTs, training, advisory contact	Reduces uncertainty and improves knowledge	Can improve productivity and economic returns	Madhushekar <i>et al.</i> , (2021); Varshney <i>et al.</i> , (2022)
Social factors	Farmer groups, peer learning, networks	Facilitates diffusion	Supports wider horizontal spread	Madhushekar <i>et al.</i> , (2021)
Technology characteristics	Relative advantage, compatibility, complexity	Determines perceived usefulness	Influences willingness to adopt and continue	Rogers (1988); Karbo <i>et al.</i> , (2024)
Pest and production risk	Pest pressure, weed competition, climate risk	Influences risk perception	Affects productivity and profitability	Narendar <i>et al.</i> , (2022); Das <i>et al.</i> , (2026a,b)
Digital factors	Digital literacy, access, trust	Determines use of digital advisory	Can improve timeliness of farm decisions	Cerjak <i>et al.</i> , (2025); Li <i>et al.</i> , (2022)

Evidence from Telangana shows that FLDs supported by on-farm trials, training, field days and exposure visits promoted adoption and horizontal spread of drum-seeded direct-seeded rice (Madhushekar *et al.*, 2021). Similarly, demonstrations on integrated nutrient management in groundnut improved yield and economic outcomes (Madhushekar *et al.*, 2022b), while FLDs on integrated crop management in watermelon demonstrated benefits under farmers' field conditions (Madhushekar *et al.*, 2022a). Red gram demonstrations also improved productivity and economic returns while reducing technology and extension gaps (Narendar *et al.*, 2023). These findings indicate that FLDs are more effective when combined with training, economic evaluation and follow-up support.

On-Farm Testing (OFTs):

On-farm testing (OFT) evaluates technologies under farmers' actual soil, climate, resource and management conditions. It enables researchers and extension personnel to identify location-specific limitations and incorporate farmer feedback before wider dissemination (Varshney *et al.*, 2022). OFTs are particularly useful for technologies that require adaptation to local labour availability, input access and farming systems, thereby improving their practical relevance and acceptability.

Farmer Training and Capacity Building:

Training converts awareness into the knowledge and

skills required for correct and sustained technology use. Farmer training, field days and exposure visits can improve technical understanding and confidence, particularly for unfamiliar technologies (Varshney *et al.*, 2022). Recent evidence from cluster demonstrations also indicates that training and continued interaction with extension agencies can improve technology adoption among beneficiary farmers.

ICT and Digital Extension:

ICT-based services, including mobile applications, SMS, call centres and digital advisory platforms, can extend the reach and timeliness of conventional extension. The usability and perceived usefulness of agricultural mobile applications also influence farmers' engagement with digital advisory services (Adesiji *et al.*, 2024). Farmers' adoption of ICT is also influenced by socio-economic characteristics and access conditions, indicating that digital availability alone does not guarantee effective use (Mehar, 2016). Their effectiveness depends on perceived usefulness, digital familiarity, connectivity, language, digital literacy and farmer trust (Cerjak *et al.*, 2025; Li *et al.*, 2022; Kishore Kumar *et al.*, 2026). Digital extension is therefore best used as a complement to face-to-face advisory services, particularly when farmers need timely and location-specific information (Mane *et al.*, 2023).

Farmer Field Schools and Participatory Pest-Management Approaches:

Farmer Field Schools (FFSs) promote experiential learning by involving farmers in crop and pest observation, diagnosis and management decisions. This approach is particularly useful for integrated pest management, where effective adoption requires repeated monitoring and timely decisions. Evidence from rice shows that extension-led demonstrations integrating agronomic practices, pest management and farmer learning can reduce brown planthopper pressure while improving productivity and profitability (Narendar *et al.*, 2022). Participatory pest-management approaches can therefore strengthen farmers' decision-making capacity and reduce dependence on unnecessary pesticide applications.

Overall Contribution of Extension to Technology Adoption:

Agricultural extension contributes to technology adoption through a combination of field demonstration, local validation, farmer training, continued technical support, digital advisory services and participatory learning. The effectiveness of these mechanisms is enhanced when technologies are demonstrated under farmers' conditions and their agronomic, economic and practical benefits are clearly communicated. Evidence across rice, groundnut, red gram, cotton and watermelon indicates that effective extension interventions can influence not only technology adoption but also crop productivity, profitability, knowledge development and farmer-to-farmer diffusion (Madhushekar *et al.*, 2021, 2022a,b, 2025a,b; Narendar *et al.*, 2022, 2023). Extension therefore serves as an important pathway through which research-based technologies can be translated into measurable farm-level outcomes. Selected agricultural extension interventions and their effects on crop productivity and farm economics are presented in Table 3.

Adoption of Major Agricultural Technologies

Improved Varieties:

Improved and locally suitable varieties can increase productivity and resilience. Extension services support their adoption through demonstrations, farmer training and information on varietal performance. However, adoption may be influenced by seed availability, cost, risk and farmers' preference for familiar varieties (Varshney *et al.*, 2022; Kurbah *et al.*, 2025). Locally relevant demonstrations and reliable seed supply can therefore support wider adoption.

Nutrient Management:

Soil-test-based fertilizer recommendations, balanced

fertilization and integrated nutrient management (INM) can improve nutrient-use efficiency and crop productivity. Their adoption depends on farmers' knowledge, input costs, access to soil-testing facilities and expected economic returns. Extension can promote these practices through field demonstrations and location-specific recommendations. Evidence from rice and groundnut also demonstrates the benefits of improved nutrient-management practices for crop performance and profitability (Madhushekar *et al.*, 2022b; Nalla Sai Suchitha *et al.*, 2025).

Weed Management:

Weed-management technologies include cultural, mechanical and chemical methods, with their effectiveness depending on timely and appropriate application. Adoption is influenced by labour availability, machinery access, input costs and knowledge of correct herbicide use. Studies on rice-fallow sunflower and direct-seeded rice demonstrate the importance of integrated weed-management practices for improving crop performance and returns (Jannu & Narendar, 2023; Das *et al.*, 2026a,b; Narendar *et al.*, 2026). Extension support is particularly important for selecting appropriate methods and ensuring their correct application.

Pest and Disease Management:

Integrated pest management (IPM) combines pest monitoring, agronomic practices, biological and chemical control and timely decision-making. Adoption requires adequate knowledge of pest identification and appropriate management options. Field evidence from rice and cotton shows that integrated pest-management interventions can reduce pest pressure while improving productivity and economic returns (Narendar *et al.*, 2022, 2023). Extension therefore plays an important role in promoting pest-management technologies as integrated packages rather than individual control measures.

Mechanization and Precision Agriculture:

Mechanization can reduce labour requirements, drudgery and delays in farm operations. Its adoption is influenced by machinery cost, farm size, land fragmentation, credit availability and access to custom-hiring or service providers (Tanti *et al.*, 2023; Van Loon *et al.*, 2020). Precision agriculture further uses sensors, remote sensing, drones, GPS, IoT and AI for crop monitoring and efficient resource management (Almazmomi, 2025). Integration of explainable AI with blockchain has also been proposed to improve decision-making and data security in smart agriculture (Chen *et al.*, 2023; Rehman *et al.*, 2023). Adoption of precision agriculture is also influenced by farmers' perceptions,

Table 3: Agricultural extension interventions and their effects on crop productivity and farm economics.

Crop	Technology/intervention	Extension mechanism	Major outcome/dimension	Illustrative evidence
Rice	Drum-seeded direct-seeded rice	FLD, training, field days and exposure visits	Technology adoption and horizontal spread	Madhushekar <i>et al.</i> , (2021)
Groundnut	Improved production/INM practices	FLD	Yield improvement and economic benefits	Madhushekar <i>et al.</i> , (2022b)
Red gram	Improved production technology	FLD	Yield, economics and yield-gap reduction	Narendar <i>et al.</i> , (2023b)
Cotton	High-density planting system	FLD and extension interventions	Productivity, farmer knowledge and wider dissemination	Madhushekar <i>et al.</i> , (2025a,b); Narendar <i>et al.</i> , (2023a)
Watermelon	Integrated crop management	FLD	Crop performance and economic outcomes	Madhushekar <i>et al.</i> , (2022a)
Rice	Brown planthopper management	Integrated pest-management demonstration	Pest reduction, productivity and profitability	Narendar <i>et al.</i> , (2022)
Cotton	Pink bollworm management	IPM/FLD approach	Pest management, yield and economic returns	Narendar <i>et al.</i> , (2023)
Sunflower	Integrated weed management under rice-fallow conditions	Field-based technology demonstration	Weed suppression, nutrient uptake, yield and economics	Das <i>et al.</i> , (2026a,b)
Agriculture	Smart and precision agriculture technologies	Technology and digital extension	Resource-use efficiency and smart crop management	Sai Satish <i>et al.</i> , (2025)

resource conditions and willingness to adopt cleaner production practices (Nguyen *et al.*, 2023). Smart agricultural technologies can improve precision and resource-use efficiency, but high investment, technical complexity and limited digital skills remain important barriers (Friha *et al.*, 2021; Subeesh & Mehta, 2021; Safeer *et al.*, 2024; Sai Satish *et al.*, 2025).

Climate-Smart Technologies:

Climate-smart technologies include improved varieties, efficient water management, conservation practices, modified planting schedules and other approaches that improve productivity and resilience. Adoption is influenced by climate-risk perception, access to information, institutional support, input availability and expected economic benefits (Mallappa & Pathak, 2023; Mishra *et al.*, 2025). Evidence from eastern India indicates that climate-smart practices can improve productivity and farm income (Tanti *et al.*, 2024). Crop diversification and supportive markets can further strengthen the adoption of climate-resilient cropping systems (Suresh *et al.*, 2026).

Constraints in Technology Adoption:

“Smart agricultural technologies can improve precision and resource-use efficiency, but high investment, technical complexity and limited digital skills remain important barriers (Friha *et al.*, 2021; Subeesh & Mehta, 2021; Safeer *et al.*, 2024; Sai Satish *et al.*, 2025).”

Technical and Knowledge Constraints:

Limited awareness, inadequate training, technological complexity and insufficient technical support can restrict correct and sustained adoption. Farmers may face particular difficulties with technologies requiring precise timing, dosage, machinery operation or integration of several practices (Dissanayake *et al.*, 2022; Varshney *et al.*, 2022). Evidence from paddy farmers identified lack of awareness, inadequate training and complexity of climate-smart practices as important constraints, while Jat *et al.*, (2025) also highlighted the importance of technology awareness and training for climate-resilient technology adoption. In Telangana, inadequate knowledge of pest and disease management was identified as a major constraint among sugarcane farmers (Narendar *et al.*, 2025).

Economic and Resource Constraints:

High initial investment, input costs, labour expenses, limited access to credit and uncertain returns can discourage adoption, particularly among smallholders. These constraints are important for mechanization and precision technologies, where service-based machinery can reduce the investment burden (Tanti *et al.*, 2023; Van Loon *et al.*, 2020). Evidence from Haryana and Bihar similarly identified production costs and initial investment as important barriers to climate-smart and resource-conserving technologies (Mishra *et al.*, 2024; Jat *et al.*, 2025; Mishra *et al.*, 2026). Labour costs and shortages

Table 4: Major constraints to technology adoption and corresponding extension strategies.

Constraint category	Illustrative problem	Effect on adoption/crop production	Extension response	Illustrative evidence
Technical	Lack of knowledge and incorrect application	Poor technology performance	Training, FLDs, OFTs and follow-up	Dissanayake <i>et al.</i> , (2022); Varshney <i>et al.</i> , (2022); Mishra <i>et al.</i> , (2024); Jat <i>et al.</i> , (2025); Narendar <i>et al.</i> , (2025)
Economic	High input, labour and machinery costs	Low adoption despite technical benefits	Demonstration of profitability; credit/service linkages	(Tanti <i>et al.</i> , 2023; Mishra <i>et al.</i> , 2024; Jat <i>et al.</i> , 2025; Narendar <i>et al.</i> , 2025)
Labour	Labour scarcity and high wages	Delayed operations & higher production cost	Mechanization and custom-hiring services	Van Loon <i>et al.</i> , (2020); Narendar <i>et al.</i> , (2025)
Pest management	Poor pest identification and control knowledge	Yield loss and excessive pesticide dependence	IPM training, FFS and pest surveillance	Narendar <i>et al.</i> , (2022, 2023a)
Weed management	Labour shortage and inadequate technical knowledge	Yield and nutrient losses	Integrated weed-management demonstrations	Das <i>et al.</i> , (2026a,b)
Social	Gender, tribal and remoteness-related barriers	Unequal access to technologies	Inclusive and targeted extension	Ahad <i>et al.</i> , (2024)
Digital	Limited connectivity and digital literacy	Restricted access to digital advisory	Digital-literacy support and hybrid extension	Cerjak <i>et al.</i> , (2025); Kishore Kr. <i>et al.</i> , (2026)
Infrastructure	Machinery, input and service gaps	Technologies cannot be implemented effectively	Custom hiring and service networks	Van Loon <i>et al.</i> , (2020); Narendar <i>et al.</i> , (2025)
Institutional	Fragmented extension actors	Poor continuity and duplication	Coordination and PPPs	Aseete <i>et al.</i> , (2023); Pandey <i>et al.</i> , (2025)

can further restrict adoption, as reported for sugarcane production in Telangana (Narendar *et al.*, 2025).

Social and Institutional Constraints:

Limited extension contact, weak farmer-group participation, gender disparities and inadequate inclusion of tribal, remote and resource-poor farmers can restrict access to technologies (Ahad *et al.*, 2024). Institutional constraints may also arise from inadequate coordination among research organizations, extension agencies, private providers and farmer organizations. Weak follow-up after demonstrations can further reduce sustained adoption. Evidence from HDPS cotton interventions highlights the importance of continued knowledge development and extension support beyond initial demonstrations (Madhushekar *et al.*, 2025a,b). Constraints in the functioning of KVKs also indicate the importance of adequate institutional capacity and operational support (Poonam & Rathore Surya, 2017).

Infrastructure and Digital Constraints:

Poor access to machinery, quality inputs, irrigation, diagnostic facilities and technical services can limit implementation even when farmers are willing to adopt a

technology. In Telangana, inadequate machinery was identified as an important infrastructural constraint in sugarcane production (Narendar *et al.*, 2025). Digital technologies face additional barriers such as poor connectivity, limited digital literacy, unequal access to devices and inadequate locally relevant content (Cerjak *et al.*, 2025; Sen *et al.*, 2024, 2025). These constraints can be particularly important for disadvantaged farmers and require greater investment in rural infrastructure, digital capacity and inclusive extension services (Nagar *et al.*, 2025).

Overall Constraints:

Technology adoption is therefore constrained by the interaction of technical knowledge, economic feasibility, social inclusion, institutional support, infrastructure and digital accessibility. These constraints are interrelated: a farmer may be aware of a technology but unable to adopt it because of high cost, lack of machinery, inadequate training or limited access to extension services. Consequently, improving adoption requires an integrated approach combining demonstration, training, economic evaluation, access to inputs and services, follow-up support and enabling institutional and policy conditions.

The major constraints limiting agricultural technology adoption and the corresponding extension strategies for addressing these constraints are summarized in Table 4.

Strategies to Improve Technology Adoption:

Overcoming technology-adoption constraints requires a shift from simple dissemination of recommendations toward farmer-centred, economically informed and continuous extension support. Strategies should address the technical, economic, social, institutional and digital barriers identified above.

Strengthening Extension Services:

Strengthening the human-resource and operational capacity of public extension is fundamental to improving technology adoption. Adequate staffing, regular frontline demonstrations, on-farm testing, timely advisory services and stronger research–extension linkages can improve the continuity and effectiveness of technology dissemination. Evidence from KVK-based interventions indicates that repeated extension contact can be more effective in sustaining adoption than one-time demonstrations (Varshney *et al.*, 2022; Steinke *et al.*, 2021). Experiences from DSR, groundnut, watermelon and HDPS cotton demonstrations further indicate the value of combining field demonstrations with farmer training, field visits and follow-up support (Madhushekar *et al.*, 2021, 2022a,b, 2025a,b). This integrated approach allows farmers to observe technology performance while receiving the technical support needed for implementation.

Economic and Farmer-Centred Technology Promotion:

Extension programmes should present technologies not only in terms of agronomic performance but also in relation to cost, profitability, labour requirements and production risk. Demonstrations that quantify yield, gross returns, net returns and benefit–cost ratio can make adoption decisions more transparent to farmers (Mittal & Tripathi 2009). Evidence from red gram, groundnut and cotton demonstrates the value of linking productivity improvements with economic outcomes (Narendar *et al.*, 2023; Madhushekar *et al.*, 2022b, 2025a,b). Technology promotion should therefore be accompanied by information on input requirements, expected returns, labour savings and potential risks. Access to credit, machinery services, quality inputs and markets should also be integrated with technology promotion, particularly for smallholders.

Digital and AI-Enabled Advisory:

Digital technologies can improve the reach and timeliness of agricultural extension by providing farmers

with mobile-based information, advisory services and digital learning opportunities. Mobile phones and ICT tools can help overcome limitations of conventional face-to-face extension and improve access to technical information (Fu & Akter, 2016; Steinke *et al.*, 2021; Giulivi *et al.*, 2023). However, limited connectivity, digital literacy, access to devices and awareness can restrict the use of digital extension services (Sen *et al.*, 2024; Sen *et al.*, 2025). Recent advances in artificial intelligence, IoT and chatbot-based advisory systems offer opportunities for more timely and personalized farm recommendations (Subeesh & Mehta, 2021; High *et al.*, 2026; Roy *et al.*, 2026). These technologies should complement human extension services, particularly where local knowledge, validation and farmer trust are important.

Capacity Building and Participatory Approaches:

Continuous, practical training is essential for sustained technology adoption. Frontline demonstrations, Farmer Field Schools, field days, exposure visits and farmer-to-farmer learning help farmers understand technologies under local conditions and build confidence in their use (Varshney *et al.*, 2022). Participatory approaches also allow farmers to provide feedback and improve the suitability of technologies (Ahad *et al.*, 2024). Evidence from demonstrations shows that repeated training and follow-up support can strengthen adoption (Madhushekar *et al.*, 2021, 2022a,b, 2025a,b).

Public–Private Partnerships:

Public–private partnerships can combine the reach of public extension with the technical expertise, resources and market linkages of private organizations. Such partnerships can support technology dissemination, training, input access and market connections (Moreddu, 2016; Aseete *et al.*, 2023; Pandey *et al.*, 2025). Effective coordination, transparency and quality assurance are necessary to ensure that commercial interests do not compromise farmers' access to reliable advice (Aseete *et al.*, 2023).

Policy and Institutional Support:

Sustained adoption requires supportive policies, adequate extension personnel and improved rural infrastructure. Investment in digital connectivity, diagnostic facilities, custom-hiring services and affordable inputs, together with stronger coordination among research, extension, private organizations and farmer groups, can improve technology delivery. Digital extension also requires attention to digital literacy, information quality, data protection and institutional readiness (Steinke *et al.*, 2021; Sen *et al.*, 2024, 2025; Mulungu *et al.*, 2025). Digital tools should therefore complement, rather than

replace, human-centred extension services.

Integrated Strategy for Sustainable Adoption:

The evidence indicates that no single intervention is sufficient to achieve sustained technology adoption. A more effective approach combines technical guidance, field demonstration, economic evaluation, capacity building, digital support, service access and institutional coordination. Extension systems should therefore move beyond simply communicating which technologies should be adopted and also demonstrate why they are beneficial, how they should be implemented, what resources are required, and under which conditions they are technically and economically feasible. Such an integrated approach can improve not only initial adoption but also continued use, farmer-to-farmer diffusion and the realization of productivity, profitability and sustainability benefits.

Future Perspectives

AI and Smart Extension:

Artificial intelligence (AI), machine learning and digital advisory platforms are likely to become increasingly important in agricultural extension by providing timely, personalized and location-specific recommendations. However, the readiness and competence of extension professionals to use AI-based technologies will influence their practical integration into advisory services (Deji *et al.*, 2023). Potential applications include crop and pest diagnosis, weather-based advisories, yield prediction and decision support (Gupta & Pal, 2025; Neeraja *et al.*, 2026). Generative AI and chatbot-based advisory systems may further improve interactive information delivery (Roy *et al.*, 2026; High *et al.*, 2026). However, accuracy, local-language capability, quality of training data and farmer trust must be addressed. AI should therefore complement rather than replace human extension personnel, particularly for field-level interpretation and practical support (Kishore Kumar *et al.*, 2026).

Climate-Resilient and Resource-Efficient Technologies:

Future extension should increasingly promote technologies that simultaneously improve productivity, profitability and climate resilience. Climate-resilient varieties, efficient water management, conservation practices, precision nutrient management, improved weed management and integrated pest management will become increasingly important (Mishra *et al.*, 2025; Tanti *et al.*, 2024). Crop diversification can further strengthen resilience and economic sustainability, particularly when supported by appropriate markets and policies (Suresh *et al.*, 2026). Integration of IoT, remote sensing, AI and

smart-farming tools with extension can improve real-time monitoring and resource-use decisions. However, these technologies need to be adapted to smallholder conditions and supported by appropriate infrastructure and technical capacity (Friha *et al.*, 2021; Subeesh & Mehta, 2021; Safeer *et al.*, 2024).

Farmer-Centred and Inclusive Extension:

Future extension systems should move beyond a predominantly technology-transfer model towards farmer-centred, participatory and inclusive approaches. Farmer Field Schools, on-farm testing, demonstrations, farmer groups and farmer-to-farmer learning can support local evaluation and adaptation of technologies. Greater attention is also needed for women, smallholders and resource-constrained communities who may have limited access to conventional and digital extension services (Ahad *et al.*, 2024). Gender-responsive digital approaches can help reduce inequalities in access to advisory services (Ragetlie *et al.*, 2022; Mutuku *et al.*, 2026).

Integrated Economic and Pest-Management Advisory:

Future advisory systems should integrate agronomic, economic, weed and pest-management information rather than providing these services separately. Farmers need to understand the expected returns, labour requirements, production risks and management implications of a technology. Evidence from rice, groundnut, watermelon, red gram and cotton demonstrates the value of evaluating technologies through both productivity and economic outcomes (Madhushekar *et al.*, 2021, 2022a,b, 2025a,b; Narendar *et al.*, 2023a,b). Integrated brown planthopper management further demonstrates the importance of linking pest suppression with crop productivity and profitability (Narendar *et al.*, 2022).

Research Priorities

Future research should move beyond short-term measurements of awareness and adoption towards long-term assessment of technology retention, dis-adoption, farmer-to-farmer diffusion, economic sustainability and equity. Research should also examine institutional readiness and responsible innovation, including how publicly funded research and extension organizations can govern emerging digital technologies (Regan, 2021). Greater attention is also needed to evaluate AI-enabled advisory systems, gender and digital inclusion, and the integration of IoT, remote sensing and blockchain into extension workflows (Zheng & Ma, 2023; Giulivi *et al.*, 2023; Neeraja *et al.*, 2026; High *et al.*, 2026; Safeer *et al.*, 2024; Friha *et al.*, 2021). Future studies should also examine whether smartphone-based information access

translates into measurable improvements in farm performance and decision-making (Zheng & Ma, 2023). Data governance, farmer consent and protection of farm-level information should also become important research priorities (Abate *et al.*, 2023).

Conclusion

Agricultural extension in India is increasingly shifting from conventional technology transfer towards participatory, pluralistic and digitally supported approaches. Effective adoption depends not only on technology availability but also on farmers' knowledge, economic capacity, resource access, institutional support and perceived benefits. Frontline demonstrations, on-farm testing, training, farmer-to-farmer learning and digital advisory services can strengthen technology adoption when combined with continued field-level support. Emerging tools such as AI, IoT, remote sensing and precision agriculture offer new opportunities for timely and location-specific advisory services, but their benefits will depend on affordability, digital literacy, infrastructure, data quality and farmer trust. Future extension systems should therefore combine human-centred advisory services with appropriate digital technologies, while giving greater attention to smallholders, women and resource-constrained farmers. Stronger institutional coordination, public-private partnerships and supportive policies will be essential for building an extension system that is inclusive, climate-resilient, economically viable and capable of sustaining agricultural innovation.

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