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Bridging the research-farmer gap: Innovations in agricultural extension systems

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Abstract

Agricultural extension systems play a vital role in transferring scientific innovations, technical knowledge, and improved farming practices from research institutions to farming communities. However, a persistent gap between agricultural research and practical farm-level adoption continues to limit productivity, sustainability, and rural development, particularly among smallholder farmers in developing countries. This critical review examines recent innovations in agricultural extension systems and evaluates their effectiveness in bridging the research-farmer gap. The review adopted a narrative approach supported by systematic procedures, drawing evidence from peer-reviewed studies, policy reports, and empirical research published between 2000 and 2025. The analysis focused on three major innovation domains: digital and ICT-based tools, institutional reforms, and participatory extension approaches. Findings indicate that mobile advisory services, artificial intelligence, social media platforms, and climate-smart digital tools have significantly improved information dissemination, farmer engagement, and decision-making efficiency. Participatory models such as Farmer Field Schools and community-based learning approaches were found to enhance trust, local relevance, and long-term adoption of technologies. Public-private partnerships and pluralistic extension systems further strengthened outreach and service delivery. Nevertheless, challenges including digital illiteracy, infrastructural limitations, gender inequality, weak institutional coordination, and unequal technology access continue to hinder inclusive extension outcomes. The review concludes that sustainable agricultural transformation requires integrated, farmer-centered, and digitally inclusive extension systems that combine technological innovation with institutional support, participatory governance, and social equity.

Keywords: Technology transfer, ICT in agriculture, farmer advisory systems, innovation systems, knowledge dissemination

1. Introduction

1.1 Background

Agricultural extension refers to the system through which scientific knowledge, innovative practices, and technical guidance are transferred from research institutions to farmers to improve agricultural productivity and rural livelihoods. Traditionally, extension systems relied on face-to-face interactions, demonstration plots, farmer meetings, and government-led advisory services. These conventional approaches played a significant role during the Green Revolution by promoting improved seeds, fertilizers, and irrigation technologies. However, modern agriculture has become increasingly knowledge-intensive, requiring rapid dissemination of climate-smart, market-oriented, and technology-driven information. As a result, agricultural extension systems have evolved toward digital and participatory models that integrate information and communication technologies (ICTs), mobile-based advisory services, social media platforms, and innovation networks (Acker & Mbiti, 2010; Klerkx *et al.*, 2022) ^[1, 25]. Recent studies emphasize that modern extension is no longer limited to one-way communication but instead focuses on interactive knowledge exchange among researchers, extension agents, private organizations, and farming communities (Leeuwis & Aarts, 2022; Koutsouris, 2023) ^[26, 29].

1.2 The research-farmer gap

Despite major advancements in agricultural research, a substantial gap continues to exist between scientific innovations and their practical adoption at the farm level. This “research-farmer gap” is reflected in low awareness, delayed adoption of technologies, limited accessibility to advisory services, and poor adaptation of innovations to local farming conditions. One of the major reasons behind this gap is the weak linkage between research institutions and farmers, where technologies are often developed without adequately understanding farmers’ socio-economic realities and local needs (Baffoe & Matsuda, 2023) ^[6]. Institutional inefficiencies, inadequate extension personnel, and poor coordination among stakeholders further restrict effective technology transfer (Feder & Savastano, 2022) ^[15]. Socio-economic barriers such as poverty, illiteracy, gender inequality, and lack of digital access also influence farmers’ ability to adopt innovations (Ragasa *et al.*, 2022; Rao *et al.*, 2023) ^[40, 42]. Additionally, many technologies fail because they are insufficiently localized or not compatible with smallholder farming systems (Meijer *et al.*, 2022) ^[21]. Behavioral factors, including risk perception and resistance to change, further limit adoption rates (Läpple *et al.*, 2022) ^[28]. Although digital agriculture and ICT-enabled extension services have expanded rapidly, unequal access to internet

connectivity, smartphones, and digital literacy remains a major challenge, especially in developing countries (Ayim *et al.*, 2022; Prasad & Pradhan, 2023) ^[5, 38].

1.3 Importance of bridging the gap

Bridging the research-farmer gap is essential for improving agricultural productivity, ensuring food security, and enhancing rural livelihoods. Effective extension systems help farmers adopt improved crop varieties, precision farming techniques, integrated pest management practices, and climate-smart technologies, ultimately increasing productivity and profitability (Jayne *et al.*, 2023; Rakholia *et al.*, 2024) ^[22, 41]. In the context of climate change, extension services also play a crucial role in building resilience by promoting sustainable resource management, water conservation, and adaptive farming practices (Gbegbelegbe *et al.*, 2022; Hebsale Mallappa & Pathak, 2023) ^[17, 19].

Moreover, stronger linkages between research institutions and farming communities contribute to inclusive agricultural development by empowering marginalized farmers, women, and rural youth through better access to information and markets (Rao *et al.*, 2023) ^[42]. Digital platforms, mobile advisory systems, and participatory innovation approaches have demonstrated significant potential in accelerating knowledge dissemination and farmer engagement (Fabregas *et al.*, 2022; Gandhi *et al.*, 2023) ^[14, 16]. However, ensuring equitable access and farmer-centered innovation remains critical for long-term sustainability.

1.4 Objectives of the review

This review aims to critically examine recent innovations in agricultural extension systems and their role in bridging the research-farmer gap. Specifically, it seeks to identify key technological and institutional innovations, evaluate their effectiveness in improving farmer outreach and technology adoption, and suggest future pathways for strengthening linkages among researchers, extension agencies, and farming communities. The review also highlights the need for inclusive, localized, and digitally integrated extension approaches to achieve sustainable agricultural transformation.

2. Methodology

The conceptual framework shown in figure 2.1 presents the systematic methodology adopted to review innovations in agricultural extension systems aimed at bridging the research-farmer gap. The process begins with the selection of a narrative review design supported by systematic procedures to ensure reliability and transparency. Relevant literature was collected from major scientific databases, followed by a structured search strategy using predefined

keywords and Boolean operators within the 2000-2025 timeframe. Inclusion and exclusion criteria were applied to select high-quality and relevant studies. Extracted information was analyzed through thematic analysis and categorized into three major innovation domains: digital tools, institutional innovations, and participatory approaches, leading to integrated insights on extension transformation. Overall, the thematic analysis demonstrated that bridging the research-farmer gap requires an integrated extension framework that combines technological innovation with institutional coordination and farmer participation. The review highlighted that future extension systems must be inclusive, adaptive, digitally connected, and socially responsive to address evolving agricultural and climate-related challenges.

2.1 Review Design

This study adopted a narrative review approach with systematic elements to critically examine innovations in agricultural extension systems and their role in bridging the research-farmer gap. A narrative review was considered appropriate because the topic spans multiple disciplines, including agricultural extension, digital agriculture, innovation systems, rural sociology, and information and communication technologies (ICTs). At the same time, systematic procedures were incorporated to ensure transparency, reliability, and comprehensive coverage of recent literature.

The review focused on understanding how emerging extension approaches, digital tools, institutional reforms, and participatory models have transformed agricultural knowledge dissemination between researchers and farming communities. Particular emphasis was placed on identifying both opportunities and persistent challenges in connecting scientific innovations with smallholder farmers, especially in developing countries. The review also critically evaluated whether technological innovations alone are sufficient to enhance adoption or whether social, institutional, and behavioral dimensions remain equally important.

Recent studies indicate that agricultural extension systems are moving away from traditional top-down knowledge transfer models toward more interactive and innovation-oriented systems involving multiple stakeholders, including governments, private firms, researchers, farmer organizations, and digital platforms. Scholars such as Klaus Davis, Laurens Klerkx, and Cornelis Leeuwis have highlighted the need for collaborative and farmer-centered extension systems that promote co-learning, adaptability, and sustainability. The review therefore examined extension innovations not only from a technological perspective but also from social and institutional viewpoints.

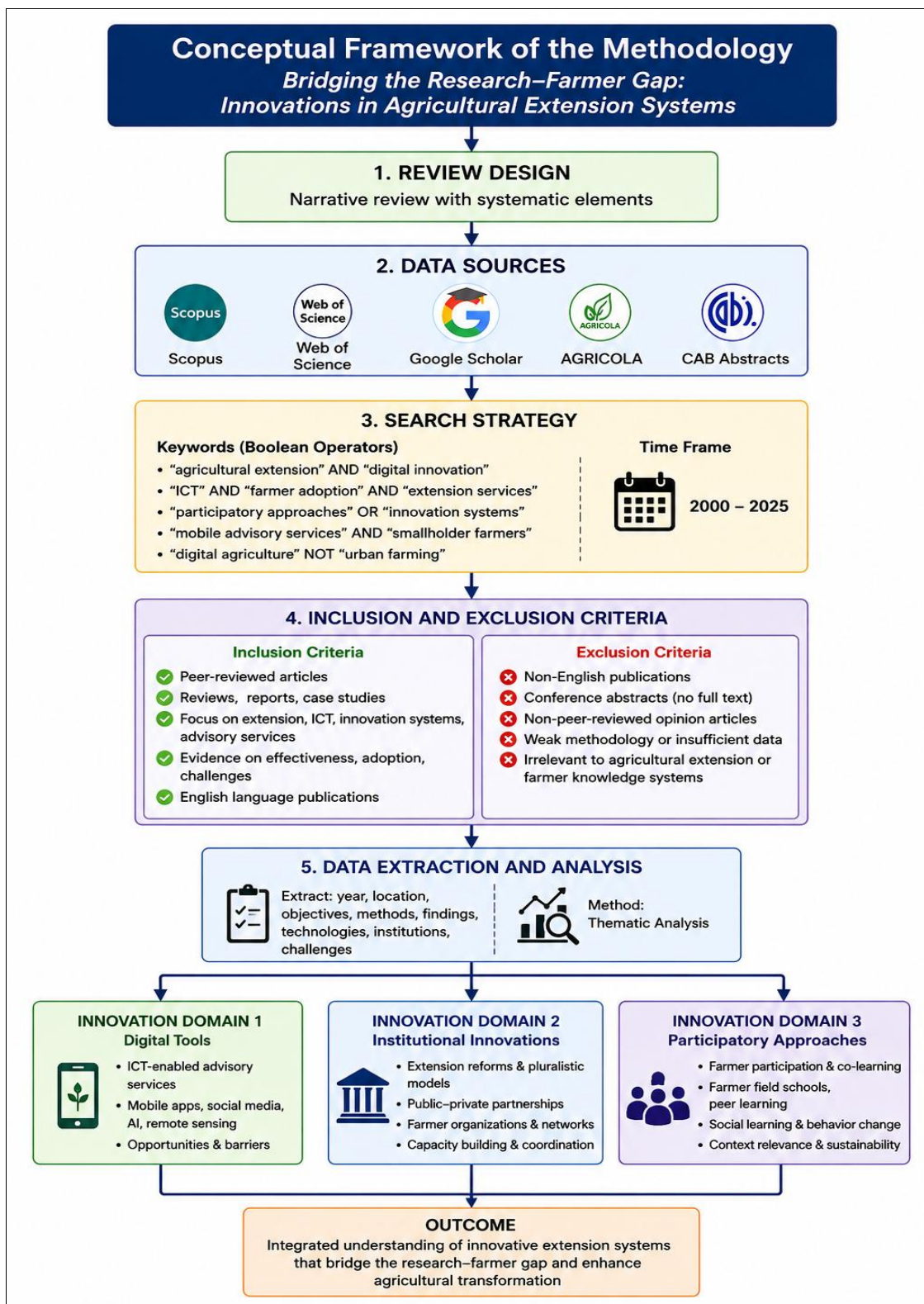


Fig 1: Conceptual framework illustrating the systematic review methodology used to evaluate innovations in agricultural extension systems for bridging the research–farmer gap

2.2 Data sources

A comprehensive literature search was conducted using major international academic databases and scholarly search engines to ensure broad coverage of peer-reviewed studies and policy-oriented literature. The primary databases consulted included Scopus, Web of Science, Google Scholar, AGRICOLA, and CAB Abstracts. These databases were selected because they provide extensive coverage of

agricultural sciences, rural development, information technology, and extension education literature.

The search strategy prioritized peer-reviewed journal articles, review papers, case studies, policy reports, and empirical research related to agricultural extension, ICT-enabled advisory services, digital agriculture, innovation systems, and farmer participation. The review also included interdisciplinary studies that explored behavioral,

institutional, and socio-economic dimensions of technology adoption.

The selected literature represented diverse geographical contexts, including Asia, Africa, Latin America, and developed agricultural economies. Particular attention was given to studies from developing countries where extension gaps are often more pronounced due to infrastructural limitations, low literacy, limited market access, and inadequate institutional support. Several recent studies from India and sub-Saharan Africa were included because these regions are currently experiencing rapid growth in mobile-based agricultural advisory services and digital extension initiatives.

2.3 Search strategy

The literature search was carried out using combinations of keywords and Boolean operators to identify relevant studies. Search terms included: “agricultural extension systems,” “digital agriculture,” “ICT in extension,” “farmer advisory services,” “technology adoption,” “innovation systems,” “participatory extension,” “mobile-based extension,” “smart farming,” “knowledge dissemination,” and “climate-smart extension.” Boolean operators such as AND, OR, and NOT were applied to refine search results and improve relevance. Examples of search combinations included:

- “Agricultural extension” AND “digital innovation”
- “ICT” AND “farmer adoption” AND “extension services”
- “Participatory approaches” OR “innovation systems” AND “agriculture”
- “Mobile advisory services” AND “smallholder farmers”
- “Digital agriculture” NOT “urban farming”

The review considered publications published between 2000 and 2025. This time frame was selected because the early 2000s marked the expansion of ICT applications in agricultural development, particularly mobile phone-based communication systems. Over the last two decades, agricultural extension has evolved significantly with the emergence of smartphones, internet connectivity, artificial intelligence, remote sensing, and social media platforms. Recent literature from 2022-2025 was especially important for capturing current trends in digital transformation and climate-smart advisory systems.

The initial search yielded a large number of articles across databases. Duplicate records were removed, and titles and abstracts were screened for relevance. Full-text articles were subsequently assessed to determine their suitability for inclusion in the review.

2.4 Inclusion and Exclusion criteria

Specific inclusion and exclusion criteria were established to maintain the quality and relevance of the review.

Inclusion criteria

The review included:

- Peer-reviewed journal articles
- Systematic reviews and meta-analyses
- Empirical case studies
- Policy-oriented research reports
- Studies focusing on agricultural extension, ICT adoption, innovation systems, and farmer advisory

services

- Publications addressing digital tools, institutional reforms, and participatory approaches in agriculture

Studies were selected if they provided evidence regarding the effectiveness, challenges, adoption patterns, or socio-economic impacts of innovative extension systems. Research examining farmer behavior, gender inclusion, climate resilience, and digital literacy was also considered relevant because these factors strongly influence extension outcomes.

Exclusion criteria

The review excluded:

- Non-English publications due to translation limitations
- Conference abstracts without full-text availability
- Non-peer-reviewed opinion articles
- Studies lacking methodological clarity
- Sources with insufficient empirical evidence or weak analytical frameworks
- Articles unrelated to agricultural extension or farmer knowledge systems

Low-quality or repetitive studies were omitted to ensure the reliability and academic rigor of the review. Preference was given to high-impact journals and well-cited publications from recognized publishers and research organizations.

2.5 Data extraction and analysis

Relevant information from the selected studies was systematically extracted and organized into thematic categories. The extracted data included publication year, study location, research objectives, methodologies used, major findings, technologies discussed, institutional arrangements, and key challenges related to agricultural extension systems.

A thematic analysis approach was employed to identify recurring concepts, emerging trends, and critical gaps in the literature. The studies were grouped into three major innovation domains:

Digital tools

This category included studies focusing on ICT-enabled advisory systems, mobile applications, social media platforms, artificial intelligence, remote sensing technologies, digital decision-support systems, and smart farming tools. Research by Marcel Fafchamps and others highlighted how mobile technologies improve farmers' access to timely information related to weather, pest outbreaks, input markets, and crop management. Similarly, studies by Rashid Fabregas and colleagues emphasized the growing importance of digital agriculture in enhancing productivity and reducing information asymmetry.

However, the analysis also identified critical barriers such as poor internet connectivity, low digital literacy, affordability constraints, and unequal access among marginalized groups. Several studies argued that digital technologies cannot independently solve extension challenges unless supported by effective institutions and localized advisory mechanisms.

Institutional innovations

This domain examined reforms in agricultural advisory systems, public-private partnerships, farmer producer organizations, pluralistic extension models, and innovation

networks. Studies demonstrated that modern extension systems increasingly rely on collaboration among governments, research institutions, agribusiness firms, non-governmental organizations, and farmer groups. Research on agricultural innovation systems emphasized that knowledge exchange is more effective when farmers actively interact with multiple actors rather than receiving information passively. Institutional flexibility, decentralization, and capacity-building programs were identified as important components for strengthening extension effectiveness and improving responsiveness to

local farming needs.

Participatory approaches

Participatory extension approaches formed the third thematic area of analysis. These approaches prioritize farmer involvement in problem identification, experimentation, and decision-making processes. Farmer field schools, community learning groups, participatory technology development, and peer-to-peer learning models were frequently discussed in the reviewed literature.

Table 1: Case study 1. Mobile-based agricultural advisory services for smallholder farmers in India

Components	Description	Supporting References
Background	Agricultural extension services in India traditionally depended on face-to-face communication, which often failed to reach remote and resource-poor farmers effectively. The emergence of ICT-enabled advisory systems created new opportunities for faster and wider dissemination of scientific agricultural knowledge.	Acker & Mbiti (2010); BIRTHAL <i>et al.</i> (2023); Shah (2022) [1, 9, 45]
Major Problem	Farmers experienced delayed access to information regarding pest outbreaks, fertilizer use, weather forecasting, and market prices. Limited extension manpower further widened the gap between research institutions and farming communities.	Feder & Savastano (2022); Prasad & Pradhan (2023) [15, 38]
Innovative Intervention	Mobile phones, SMS alerts, WhatsApp groups, digital call centers, mobile applications, and social media-based advisory platforms were introduced to provide real-time agricultural guidance in local languages.	Alam & Shaba (2022); Gandhi <i>et al.</i> (2023); Tripathi (2023) [3, 16, 51]
Implementation Strategy	Agricultural universities, extension agencies, agri-tech firms, and government departments collaborated to distribute weather-based advisories, crop management recommendations, and market intelligence directly to farmers through digital platforms.	Chandra <i>et al.</i> (2023); Khatri <i>et al.</i> (2024) [11, 23]
Observed Outcomes	Farmers gained timely access to scientific recommendations, resulting in improved crop management, higher technology adoption, better farm productivity, and stronger climate resilience. Digital tools also improved interaction between scientists and farmers.	Mittal & Mehar (2023); Mukherjee <i>et al.</i> (2025); Zhang <i>et al.</i> (2022) [32, 33, 56]
Key Challenges	Poor internet connectivity, digital illiteracy, affordability issues, and low trust in digital systems limited adoption among certain farmer groups, especially elderly and marginal farmers.	Prasad & Pradhan (2023); Shinde <i>et al.</i> (2025) [38, 47]
Key Learning	Integrating digital technologies with conventional extension approaches creates more inclusive and efficient agricultural advisory systems. Farmer training and localized content are essential for sustainability.	Alam & Shaba (2022); Sharma <i>et al.</i> (2025) [3, 46]
Overall Conclusion	ICT-enabled extension systems have significantly contributed to bridging the research-farmer gap in India by improving information accessibility, communication efficiency, and farmer participation in agricultural innovation systems.	BIRTHAL <i>et al.</i> (2023); Gandhi <i>et al.</i> (2023) [9, 16]

Table 2: Case study 2. Climate-smart digital extension systems in sub-Saharan Africa

Components	Description	Supporting References
Background	Many African countries face challenges such as weak extension infrastructure, climate variability, and poor access to agricultural innovations. Digital extension systems emerged as an important strategy to strengthen communication between researchers and farmers.	Ayim <i>et al.</i> (2022); Baffoe & Matsuda (2023) [5, 6]
Major Problem	Conventional extension systems were unable to effectively serve geographically dispersed farming populations due to shortages of trained personnel and financial limitations.	Jayne <i>et al.</i> (2023); Wossen <i>et al.</i> (2023) [22, 53]
Innovative Intervention	Mobile advisory platforms, interactive voice response systems, digital climate advisories, radio-supported learning, and farmer knowledge-sharing networks were introduced to improve agricultural communication.	Choruma <i>et al.</i> (2024); Byamukama <i>et al.</i> (2025) [10, 12]
Implementation Strategy	Governments, NGOs, research organizations, and private institutions collaborated to provide localized climate information, pest alerts, soil management guidance, and market-related advisories using ICT platforms.	Gbegbelegbe <i>et al.</i> (2022); Xu <i>et al.</i> (2023) [17, 54]
Observed Outcomes	Farmers adopting digital advisory services demonstrated better awareness of climate-smart agricultural practices, improved input management, increased resilience to climatic shocks, and higher adoption of improved technologies.	Hebsale Mallappa & Pathak (2023); Fabregas <i>et al.</i> (2022) [14, 19]
Key Challenges	Limited electricity supply, unequal smartphone access, gender disparities in technology ownership, weak digital literacy, and institutional coordination problems reduced the effectiveness of extension systems.	Ragasa <i>et al.</i> (2022); Rao <i>et al.</i> (2023); Yekinni <i>et al.</i> (2023) [40, 42, 55]
Key Learning	Successful extension reform requires inclusive digital infrastructure, participatory communication approaches, gender-sensitive policies, and integration of indigenous and scientific knowledge systems.	Klerkx & Begemann (2022); Leeuwis & Aarts (2022) [24, 29]
Overall Conclusion	Climate-smart digital extension systems in Africa have strengthened farmer decision-making, enhanced knowledge exchange, and narrowed the research-farmer gap by accelerating access to agricultural innovations and advisory services.	Baffoe & Matsuda (2023); Wossen <i>et al.</i> (2023) [6, 53]

Studies on social learning and behavioral adoption revealed that farmers are more likely to adopt innovations when they observe successful implementation within their communities. Participatory systems also enhance trust, contextual relevance, and long-term sustainability. Nevertheless, the review found that participatory approaches require strong facilitation skills, institutional support, and sustained investment to remain effective at scale.

3. Critical analysis and results with discussion

3.1 Traditional extension systems: limitations

Agricultural extension systems have historically played a central role in transferring scientific knowledge from research institutions to farming communities. Conventional extension models, particularly in developing countries, were largely characterized by top-down communication structures where experts generated recommendations and farmers were expected to adopt them without substantial participation in decision-making. Although these systems contributed significantly to the spread of Green Revolution technologies, they often failed to address the diverse socio-economic, ecological, and cultural realities of smallholder farmers.

One major limitation of traditional extension systems has been their centralized and hierarchical nature. Information generally flowed in one direction from researchers to extension officers and then to farmers leaving little opportunity for farmers to share indigenous knowledge, local experiences, or feedback. Leeuwis and Aarts (2022)^[29] argued that innovation cannot be sustained through linear communication alone because agricultural challenges are highly context-specific and dynamic. Similarly, Feder and Savastano (2022)^[15] emphasized that many public extension services continue to operate with outdated communication structures that inadequately reflect farmers' actual needs.

Another challenge has been the limited reach and scalability of conventional extension mechanisms. In many low-income countries, extension worker-to-farmer ratios remain extremely low, resulting in poor coverage of remote rural communities. Davis *et al.* (2023)^[13] observed that extension personnel often lack adequate transportation, technical resources, and institutional support, reducing the effectiveness of field-based advisory systems. As agricultural systems become more knowledge-intensive, the inability of traditional models to rapidly disseminate information has become increasingly problematic.

A further limitation involves weak feedback and evaluation mechanisms. Traditional systems frequently measured success based on the number of visits or demonstrations conducted rather than actual farmer outcomes, adoption rates, or livelihood improvements. This created a disconnect between extension objectives and practical farm realities. Consequently, many technologies promoted through conventional systems failed to achieve widespread adoption because farmers perceived them as economically risky, labor-intensive, or poorly suited to local conditions.

3.2 Emerging innovations in agricultural extension

3.2.1 Digital and ICT-based innovations

The rapid advancement of information and communication technologies (ICTs) has transformed agricultural extension from a predominantly face-to-face activity into a more connected, data-driven, and interactive system. Digital tools

now facilitate real-time communication, personalized advisory services, and wider dissemination of agricultural knowledge.

Mobile advisory services represent one of the most influential innovations in agricultural extension. SMS-based advisories, smartphone applications, and voice messaging systems enable farmers to receive timely information regarding weather, pest outbreaks, fertilizer application, and market prices. Acker and Mbiti (2010)^[1] highlighted how mobile phone penetration in Africa significantly improved information access and reduced communication barriers for rural populations. Recent studies by Gandhi *et al.* (2023)^[16] and Mukherjee *et al.* (2025)^[33] further demonstrated that mobile-based extension services improve farmers' responsiveness to climatic and market uncertainties.

Artificial intelligence (AI)-based decision support systems are also gaining importance in modern agriculture. These systems integrate machine learning algorithms, weather forecasts, soil information, and crop models to generate precise farm recommendations. Xu *et al.* (2023)^[54] noted that AI-powered platforms can support farmers in pest diagnosis, irrigation scheduling, and yield prediction, thereby increasing production efficiency. Likewise, remote sensing and GIS technologies now enable extension agencies to monitor crop health, drought conditions, and land-use patterns at large scales.

Social media platforms and online communities have additionally emerged as informal extension channels. Platforms such as WhatsApp, YouTube, Facebook, and Telegram allow farmers to exchange experiences, access tutorial videos, and interact directly with experts. Tham-Agyekum *et al.* (2023)^[49] reported that social media has strengthened peer learning and accelerated the diffusion of agricultural innovations among younger farmers.

Despite these benefits, significant concerns remain regarding accessibility and the digital divide. Digital innovations often favor literate, resource-rich, and technologically connected farmers, while marginalized groups may remain excluded. Chandra *et al.* (2023)^[11] and Prasad and Pradhan (2023)^[38] found that poor internet connectivity, low digital literacy, and affordability constraints continue to limit ICT adoption in rural regions. Therefore, while digital extension is highly scalable and cost-effective, its inclusiveness remains uneven.

3.2.2 Farmer-centric and participatory approaches

In response to the shortcomings of conventional extension systems, participatory and farmer-centered approaches have gained substantial attention. These approaches recognize farmers not merely as recipients of knowledge but as active contributors to innovation processes.

Farmer Field Schools (FFS) are among the most successful participatory models. Through group-based experiential learning, farmers collectively observe field conditions, conduct experiments, and evaluate management practices. This method enhances farmers' analytical skills and encourages local problem-solving. Studies have shown that FFS approaches improve adoption rates because farmers gain practical experience and confidence before implementing technologies independently.

Participatory Rural Appraisal (PRA) methods similarly encourage community involvement in identifying local challenges and designing agricultural interventions. Klerkx and Begemann (2022)^[24] emphasized that co-creation of

knowledge between researchers, extension agents, and farmers leads to more relevant and adaptable innovations. Rather than transferring fixed technologies, participatory systems facilitate continuous learning and adaptation.

The effectiveness of participatory extension approaches lies in their ability to generate context-specific solutions. BenYishay and Mobarak (2022) ^[8] found that social learning significantly influences technology adoption, particularly when farmers observe positive outcomes among peers. Participatory systems therefore enhance trust, strengthen social networks, and reduce perceived risks associated with innovation adoption.

However, participatory approaches are often time-consuming and resource-intensive. Scaling such models across large populations remains challenging because they require skilled facilitators, sustained engagement, and institutional commitment. Nevertheless, their emphasis on empowerment and local relevance makes them highly valuable for sustainable agricultural transformation.

3.2.3 Public-Private Partnerships (PPP) models

Public-private partnerships (PPPs) have increasingly emerged as alternative mechanisms for delivering agricultural extension services. Governments, agribusiness firms, NGOs, research institutions, and agri-tech startups now collaborate to improve knowledge dissemination and service delivery.

Agri-tech startups play a particularly important role in digital extension ecosystems. Many startups provide farmers with mobile-based crop advisories, e-commerce platforms, weather intelligence, and precision farming tools. BIRTHAL *et al.* (2023) ^[9] observed that ICT-led agricultural transformation in India has been strongly driven by private-sector innovation and investment.

Contract farming arrangements also provide embedded extension services where companies supply technical guidance, quality standards, and market linkages to farmers. Such arrangements can improve productivity and reduce market uncertainty. NGO-led extension initiatives further contribute by targeting marginalized communities often neglected by state systems.

Despite these advantages, PPP models raise concerns regarding equity and inclusiveness. Glover *et al.* (2023) ^[18] argued that digital agriculture initiatives sometimes reinforce existing power imbalances because private companies prioritize commercially profitable farmers and regions. Smallholders lacking purchasing power may receive limited attention. Additionally, dependency on donor funding or private investment raises questions regarding the long-term sustainability of some PPP initiatives.

Thus, while PPPs improve efficiency, innovation, and service reach, regulatory frameworks are necessary to ensure accountability, transparency, and equitable access.

3.2.4 Institutional and Policy innovations

Institutional reforms have become increasingly important in strengthening extension systems. Decentralized extension structures allow local governments and communities to participate more actively in agricultural planning and implementation. Such systems are often more responsive to local agroecological and socio-economic conditions.

Pluralistic extension frameworks, involving multiple actors from public, private, and civil society sectors, are also

gaining prominence. Koutsouris (2023) ^[26] noted that pluralistic systems improve flexibility and innovation capacity by integrating diverse expertise and service providers. Many developing countries have introduced policy reforms aimed at modernizing extension services, promoting digitalization, and enhancing accountability.

However, governance challenges remain substantial. Coordination among multiple stakeholders is often weak, resulting in duplication of efforts and fragmented service delivery. Funding instability, bureaucratic inefficiencies, and limited institutional capacity further constrain extension reforms. Effective integration of research institutions, extension agencies, private firms, and farmer organizations remains essential for creating coherent agricultural innovation systems.

3.2.5 Climate-smart extension approaches

Climate change has intensified the need for adaptive and resilient agricultural extension systems. Climate-smart extension approaches aim to equip farmers with knowledge and tools that support sustainable production under changing climatic conditions.

Weather-based agro-advisories now provide farmers with location-specific forecasts regarding rainfall, temperature, pest outbreaks, and irrigation scheduling. Gbengelegbe *et al.* (2022) ^[17] reported that climate advisory services significantly improve farmers' preparedness and risk management capacity. Similarly, Hebsale Mallappa and Pathak (2023) ^[19] emphasized that climate-smart extension enhances the adoption of conservation agriculture, drought-tolerant varieties, and water-efficient technologies.

Risk management tools such as crop insurance advisories, early warning systems, and climate information platforms are becoming integral components of extension systems. These innovations strengthen resilience by enabling farmers to make informed decisions under uncertainty.

3.3 Comparative effectiveness of innovations

The comparative analysis of emerging extension innovations indicates that digital and participatory approaches generally outperform traditional systems in terms of adoption, scalability, and farmer engagement. ICT-enabled advisory services have demonstrated positive impacts on yield improvement, income enhancement, and market access. Mittal and Mehar (2023) ^[32] found that digital advisory systems significantly improved farm productivity through timely and customized recommendations.

Participatory approaches, while less scalable, often achieve higher long-term adoption rates because they strengthen farmer ownership and trust. Farmer-centered systems are particularly effective in promoting sustainable practices that require behavioral change and local adaptation.

PPP models improve operational efficiency and technological innovation but may produce unequal outcomes if inclusiveness is not adequately addressed. Climate-smart extension systems have shown growing effectiveness in supporting resilience under climate variability, particularly in vulnerable regions.

Overall, no single model is universally effective. Hybrid systems combining digital technologies, participatory learning, institutional coordination, and policy support appear most promising for bridging the research-farmer gap.

3.4 Key challenges identified

Despite significant progress, several barriers continue to hinder the effectiveness of innovative extension systems. Digital illiteracy remains a major challenge, especially among elderly farmers, women, and marginalized communities. Infrastructure limitations, including poor electricity supply, weak internet connectivity, and inadequate telecommunications networks, further restrict digital extension expansion.

Policy and funding constraints also weaken institutional sustainability. Many extension reforms rely heavily on external donor support, limiting long-term continuity. Gender and social inclusion issues remain particularly critical. Ragasa *et al.* (2022) ^[40] and Rao *et al.* (2023) ^[42] emphasized that women farmers often face unequal access to digital devices, training opportunities, and extension resources.

Behavioral resistance, lack of trust in digital systems, and concerns regarding data privacy additionally influence adoption patterns. Farmers may hesitate to share farm-level information due to uncertainty about data ownership and commercial misuse.

3.5 Future directions

Future agricultural extension systems are likely to become increasingly data-driven, interconnected, and farmer-responsive. The integration of AI, Internet of Things (IoT), big data analytics, and precision agriculture technologies can significantly enhance decision-making accuracy and resource-use efficiency. Smart sensors, drones, and predictive analytics will likely support real-time farm monitoring and automated advisory systems.

Strengthening last-mile connectivity will remain essential for ensuring equitable access to digital extension services. Investments in rural internet infrastructure, affordable smartphones, and localized digital content are necessary to bridge the digital divide.

Capacity building of extension personnel is equally important. Extension agents must develop competencies in digital communication, climate adaptation, data interpretation, and participatory facilitation. Continuous training and institutional support will therefore be crucial.

Finally, ethical governance of farmer data will become increasingly important in digital agriculture. Transparent policies regarding data ownership, consent, privacy, and benefit-sharing are necessary to protect farmers from exploitation and ensure trust in digital extension ecosystems.

In conclusion, innovations in agricultural extension systems have created unprecedented opportunities to bridge the long-standing gap between agricultural research and farming communities. However, technological advancement alone cannot guarantee inclusive agricultural transformation. Sustainable extension systems must integrate digital innovation with participatory governance, institutional accountability, and social equity to ensure that agricultural knowledge benefits all farmers, particularly smallholders and vulnerable populations.

Conclusion

The present review critically examined the evolving landscape of agricultural extension systems and their

contribution toward bridging the long-standing gap between agricultural research and farming communities. The findings demonstrate that traditional extension approaches, although historically important in disseminating Green Revolution technologies, are no longer sufficient to address the complex challenges of modern agriculture. Contemporary farming systems require rapid, localized, climate-responsive, and market-oriented knowledge delivery mechanisms capable of supporting diverse farming communities under changing environmental and socio-economic conditions.

The review highlights that digital and ICT-based innovations have significantly transformed extension services by enabling real-time communication, wider outreach, and personalized advisory support. Mobile applications, artificial intelligence, remote sensing technologies, social media platforms, and climate-smart advisory systems have improved farmers' access to timely and actionable information. These innovations have enhanced productivity, strengthened climate resilience, and reduced information asymmetry in many regions. However, technological advancement alone cannot guarantee effective agricultural transformation. Persistent barriers such as poor digital infrastructure, low literacy levels, affordability constraints, and unequal access to digital tools continue to exclude vulnerable and marginalized farmers from benefiting fully from modern extension systems.

Participatory and farmer-centered approaches emerged as equally important components of successful extension frameworks. Farmer Field Schools, participatory technology development, and peer-learning systems improve trust, contextual relevance, and farmer ownership of innovations. Such approaches recognize farmers as active contributors rather than passive recipients of knowledge, thereby encouraging sustainable adoption of agricultural practices. Similarly, institutional innovations and public-private partnerships have expanded extension outreach and introduced greater flexibility and efficiency into agricultural advisory systems. Nevertheless, issues related to governance, coordination, accountability, and equity remain significant concerns within pluralistic extension models.

The review further emphasizes that future extension systems must move toward integrated and inclusive innovation ecosystems where researchers, extension agencies, private organizations, digital platforms, and farming communities collaborate continuously. Investments in rural connectivity, digital literacy, capacity building of extension personnel, and ethical data governance will be essential for ensuring equitable access to agricultural knowledge. Strengthening localized and climate-smart extension services will also be critical for enhancing resilience under increasing climatic uncertainty.

Overall, bridging the research-farmer gap requires more than the diffusion of technologies; it demands socially responsive, participatory, and institutionally coordinated extension systems that place farmers at the center of innovation processes. Sustainable agricultural development can only be achieved when scientific advancements are effectively translated into practical, accessible, and locally adaptable solutions that benefit all categories of farmers, particularly smallholders, women, and resource-poor communities.

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