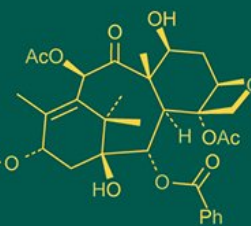
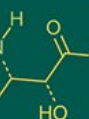
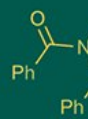


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Transformation of agricultural extension services in the digital era: Opportunities and challenges

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Abstract

Agricultural extension has historically served as the principal bridge between agricultural research and farm-level practice, yet conventional face-to-face delivery models have long struggled with limited staff strength, high recurrent costs, poor accountability and an inability to reach dispersed, smallholder-dominated farming populations in a timely manner. Over the past two decades, the proliferation of mobile telephony, the internet, geospatial and sensor technologies, and, more recently, artificial intelligence has opened a new frontier for extension and advisory services, commonly described as digital or e-extension. This review synthesizes the trajectory of agricultural extension from colonial and training-and-visit models through participatory and pluralistic approaches to the present digitally mediated ecosystem. It examines the structural limitations of traditional extension, catalogues the principal digital technologies now reshaping advisory delivery-mobile advisory platforms, interactive voice response and call centres, e-portals and mobile applications, remote sensing and precision agriculture tools, the Internet of Things, blockchain, and generative artificial intelligence and chatbot-based advisory systems-and evaluates the opportunities these technologies create for scale, personalisation, cost efficiency, climate resilience and inclusion of women and youth. It equally examines persistent constraints, including the rural digital divide, infrastructural deficits, low digital literacy, data governance and privacy concerns, content localization challenges and the risk of excluding the most vulnerable farmers. Institutional readiness, human resource capacity, regulatory and policy frameworks, and the role of public-private partnerships in scaling digital advisory ecosystems are discussed, alongside comparative case evidence from India, sub-Saharan Africa and Asia illustrating both successes and shortfalls of digital extension initiatives. The review concludes that digital technologies offer substantial promise for revitalizing agricultural extension but that this promise can be realized only through hybrid delivery models that combine digital tools with human intermediation, sustained investment in rural infrastructure and digital literacy, gender-responsive design, and coherent institutional and policy frameworks that treat digitalisation as a complement to, rather than a replacement for, the human extension workforce.

Keywords: Agricultural extension, digital extension, artificial intelligence (AI), information and communication technologies (ICT), precision agriculture, digital advisory services

1. Introduction

Agriculture continues to underpin the livelihoods, food security and economic stability of a large share of the world's population, and the timely flow of appropriate knowledge from research institutions to farming communities remains central to raising productivity, resilience and incomes. Agricultural extension and advisory services have traditionally performed this knowledge-brokering function, connecting farmers with researchers, markets and policy through field visits, demonstrations, farmer field schools and mass media (Rogers, 1988) [44]. Extension work has an ancient lineage but assumed its modern institutional form largely over the past century and a half, evolving through a succession of organisational models in response to changing agrarian, technological and political contexts (Rogers, 1988; Al-Kaisi *et al.*, 2015) [44, 5]. Despite decades of investment, conventional extension systems in many low- and middle-income countries remain characterized by a low extension-worker-to-farmer ratio, weak linkages with research institutions, insufficient operational budgets, and messages that are poorly tailored to agro-ecological and socio-economic diversity (Feder *et al.*, 1987; Steinke *et al.*, 2021) [15, 54]. These structural weaknesses have historically constrained the reach, timeliness and cost-effectiveness of advisory delivery, particularly for

smallholder, women and remote farmers who are least able to access alternative information sources. The past two decades have witnessed an unprecedented expansion of information and communication technology (ICT) infrastructure in rural areas of the developing world, driven principally by the diffusion of mobile telephony and, more recently, mobile internet and smartphone penetration (Khan *et al.*, 2025; Ndimbo *et al.*, 2025) ^[27, 36]. This has catalyzed the emergence of a distinct sub-field of digital or e-extension, encompassing mobile-based advisory platforms, interactive voice response systems, call centres, SMS-based alerts, web and mobile applications, remote sensing and geospatial decision-support tools, the Internet of Things (IoT), blockchain-enabled traceability and, most recently, generative artificial intelligence (AI) chatbots capable of delivering conversational, personalized advisory services at scale (Mulungu *et al.*, 2025; Neeraja *et al.*, 2026; Roy *et al.*, 2026) ^[31, 37, 46]. The COVID-19 pandemic served as a further inflection point, compelling extension systems worldwide to pivot rapidly toward remote and hybrid delivery modalities and accelerating institutional acceptance of digital tools that had previously been treated as peripheral innovations (Singh *et al.*, 2025; Hassoun *et al.*, 2023) ^[53, 23]. Digital transformation in agricultural extension is, however, neither uniform nor unambiguously beneficial. While digital tools promise to overcome long-standing constraints of scale, cost and timeliness, they simultaneously introduce new risks relating to the digital divide, data governance, content quality, and the potential marginalisation of farmers who lack access to devices, connectivity or digital literacy (Ragettie *et al.*, 2022; Ahad *et al.*, 2024) ^[41, 3]. A comprehensive assessment of the opportunities and challenges associated with this transformation is therefore both timely and necessary. This review accordingly (i) traces the historical evolution of agricultural extension services; (ii) analyses the structural limitations of traditional extension approaches that have motivated the search for digital alternatives; (iii) catalogues the principal digital technologies now being deployed in extension and advisory delivery; (iv) evaluates the opportunities and constraints associated with digital extension; (v) examines institutional readiness and policy frameworks required to support digitalisation; (vi) presents comparative case evidence from selected countries; and (vii) identifies priority directions for future research.

2. Evolution of Agricultural Extension Services

The term 'extension' originated in nineteenth-century England to describe university education extended beyond the campus to the wider public, and the concept was subsequently adapted to agriculture in the United States through the Smith-Lever Act of 1914, which formally established the Cooperative Extension Service within the land-grant university system (Al-Kaisi *et al.*, 2015) ^[5]. This model, built on a linear transfer-of-technology paradigm in

which research generated at experiment stations was disseminated to farmers through trained agents, was subsequently exported to much of the colonized and newly independent world during the twentieth century (Rogers, 1988) ^[44]. In the 1970s and 1980s, the World Bank promoted the Training and Visit (T&V) system as a standardized extension model across dozens of countries, characterized by a fixed calendar of agent visits to contact farmers, a single line of technical command, and regular in-service training of extension staff (Feder *et al.*, 1987) ^[15]. Empirical evaluations of T&V produced mixed results: studies in northwest India reported measurable wheat yield gains attributable to T&V extension (Feder *et al.*, 1987) ^[15], while assessments in rainfed regions of Ethiopia and elsewhere found that the system's reliance on a narrow cadre of contact farmers limited its reach to the wider farming population and that women were largely excluded from its structures (Rokvić & Vaško, 2016) ^[45]. By the late 1990s, the recurrent fiscal burden of T&V, its top-down orientation, and its poor fit with heterogeneous farming systems had prompted a broad institutional retreat from the model.

The following two decades saw a diversification of extension approaches, including participatory methods such as farmer field schools, decentralized and pluralistic advisory systems involving non-governmental organisations and private input suppliers, farmer-to-farmer and demand-driven extension, and increasing emphasis on market linkage and value-chain facilitation rather than production advice alone (Khan *et al.*, 2025) ^[27]. This period also saw growing interest in the role of ICT: early applications, including radio broadcasts, video vans and rural telecentres, provided the first non-traditional channels for reaching dispersed farming populations, laying the groundwork for the mobile- and internet-based systems that followed (Khan *et al.*, 2025) ^[27]. A systematic review of the evolution of ICT in agricultural extension over the past seven decades identifies a clear shift from one-way, linear dissemination models toward two-way, farmer-centred and co-innovation-oriented communication, driven successively by radio, television, the internet, mobile telephony and, most recently, smartphone-enabled social media and artificial intelligence (Khan *et al.*, 2025) ^[27]. This trajectory reflects a broader reconceptualization of extension itself—from a mechanism for transferring predetermined technical packages to a facilitative, networked function that connects farmers, researchers, input suppliers, financial institutions and markets within an agricultural innovation system (Davis *et al.*, 2025). The digital era represents the latest, and arguably most disruptive, phase in this long institutional evolution, one in which the extension agent is increasingly complemented, and in some functions substituted, by digital intermediaries. Table 1 summarizes this trajectory as a timeline of successive extension paradigms, their defining characteristics, and their principal limitations.

Table 1: Timeline of the evolution of agricultural extension paradigms, from land-grant transfer-of-technology models to AI-driven digital extension

Period	Dominant Paradigm	Defining Characteristics	Principal Limitation	Key Source(s)
1914-1960s	Land-grant / colonial transfer-of-technology extension	Linear, top-down dissemination from experiment stations via trained agents	Weak farmer participation; limited reach beyond demonstration plots	(Al-Kaisi <i>et al.</i> , 2015; Rogers, 1988) ^[5, 44]
1970s-1980s	Training and Visit (T&V) system	Fixed visitation calendar, single line of command, contact-farmer model	High recurrent cost; narrow reach; weak gender inclusion	(Feder <i>et al.</i> , 1987; Rokvić & Vaško, 2016) ^[15, 45]
1990s-2000s	Participatory and pluralistic extension	Farmer field schools, NGO and private-sector involvement, demand-driven advice	Fragmented coordination; uneven institutional funding	(Khan <i>et al.</i> , 2025) ^[27]
2000s-2010s	Early ICT-enabled extension	Radio, video vans, telecentres, first-generation mobile voice/SMS advisory	Limited interactivity; generic, one-way messaging	(Khan <i>et al.</i> , 2025; Oumer, 2025) ^[27, 38]
2010s-early 2020s	Mobile and e-extension	Smartphone apps, e-portals, call centres, two-way farmer-to-farmer communication	Persistent digital divide; content localization gaps	(Mulungu <i>et al.</i> , 2025; Mane <i>et al.</i> , 2023) ^[31, 29]
2020s-present	AI-driven and hybrid digital extension	Generative AI chatbots, IoT/remote-sensing data fusion, hybrid human-digital delivery	Data governance, trust and evaluation evidence still maturing	(Neeraja <i>et al.</i> , 2026; High <i>et al.</i> , 2026; Feyisa, 2020) ^[37, 24, 16]

3. Traditional Agricultural Extension: Limitations and Challenges

Notwithstanding its historical contributions, the conventional face-to-face extension model exhibits several structural limitations that have become increasingly apparent as farming populations have grown and diversified. First, extension-worker-to-farmer ratios in many developing countries remain far below recommended norms, so that even well-designed programmes can reach only a small fraction of farm households within a season (Steinke *et al.*, 2021) ^[54]. Second, the T&V and similar top-down models were frequently criticized for weak downward accountability, limited farmer participation in programme design, and messages that were poorly adapted to local agro-ecological and socio-economic conditions (Feder *et al.*, 1987) ^[15].

Third, traditional extension services have historically struggled to maintain robust linkages with agricultural research systems, resulting in a persistent gap between technologies generated at research stations and those actually recommended to farmers, compounded by inadequate numbers of subject-matter specialists able to translate research findings into field-ready advice (Feder *et al.*, 1987) ^[15]. Fourth, recurrent cost structures dependent on donor or government financing have proven fiscally unsustainable in many contexts, leading to abrupt curtailment of services once external funding lapsed (Rokvić & Vaško, 2016) ^[45]. Fifth, face-to-face extension is intrinsically constrained in its ability to deliver time-sensitive information-such as pest outbreak alerts, weather warnings or market price movements-at the speed required for farmers to act effectively, a limitation that becomes acute during crises such as pandemics, floods or locust invasions that restrict physical movement and contact-based service delivery (Mulungu *et al.*, 2025; Singh *et al.*, 2025) ^[31, 53]. Sixth, and of particular significance for equity, women farmers have historically been under-served by traditional extension structures, which have tended to interact preferentially with male household heads and 'progressive' or contact farmers, thereby reproducing and, in some contexts, widening gender gaps in access to agricultural knowledge and inputs (Rokvić & Vaško, 2016; Ahad *et al.*, 2024) ^[45, 3]. Finally, traditional extension systems have often relied on generalized, one-size-fits-all technical packages disseminated through top-down

communication, an approach poorly matched to the high heterogeneity of smallholder farming systems and to farmers' own profit and risk considerations, which do not always align neatly with yield-maximising recommendations derived from experimental research plots (Steinke *et al.*, 2021) ^[54]. These cumulative limitations of reach, cost, timeliness, accountability, gender inclusion and message relevance constitute the principal rationale for the search for complementary digital delivery mechanisms capable of overcoming the scale and cost constraints inherent in purely human-mediated extension.

4. Digital Technologies Transforming Agricultural Extension

A broad and rapidly evolving suite of digital technologies is now being deployed across the extension value chain, ranging from simple voice- and text-based mobile services to sophisticated artificial-intelligence-driven decision-support systems. These technologies can be broadly grouped into six categories: mobile-based advisory services; e-portals and mobile applications; remote sensing, geospatial and precision-agriculture tools; the Internet of Things and sensor networks; blockchain-enabled data and supply-chain systems; and artificial intelligence, machine learning and generative chatbot-based advisory systems.

4.1 Mobile-Based Advisory Services

Mobile telephony remains the most widely adopted digital channel for agricultural advisory delivery in the developing world because of its low cost, high penetration and compatibility with basic-feature handsets (Gouroubera *et al.*, 2025; Khan *et al.*, 2020) ^[20, 26]. Services in this category include voice-based interactive voice response (IVR) systems, farmer hotlines and call centers, SMS-based weather and price alerts, and voice or text advisories tailored to specific crops. India's Kisan Call Centre, established in 2004, exemplifies this model, providing farmers with toll-free, local-language access to agricultural experts, while similar national-level 'farmer hotlines' have since been established in Ethiopia and elsewhere (Oumer, 2025; Singh, 2015) ^[38, 52]. Meta-analytic evidence indicates that mobile-phone-mediated advisory services can meaningfully improve technology adoption, though effects on yield and profitability vary considerably by context and delivery design (Gouroubera *et al.*, 2025; Giulivi *et al.*, 2023) ^[20, 19].

4.2 E-Portals and Mobile Applications

Web-based e-portals and smartphone applications now provide farmers with crop-specific advisories, market price information, soil health data, government scheme information and input-marketing linkages within a single interface (Mane *et al.*, 2023) ^[29]. In India, platforms such as the Farmers' Portal and privately developed mobile applications integrate weather forecasting, crop advisory and market intelligence functions, while systematic reviews across South and Southeast Asia identify usability, perceived usefulness and trust as key determinants of sustained farmer engagement with such applications (Adesiji *et al.*, 2024; Sen *et al.*, 2024) ^[2, 49].

4.3 Remote Sensing, Geospatial and Precision-Agriculture Tools

Satellite and drone-based remote sensing, combined with geographic information systems, enable field-level monitoring of crop health, soil moisture and irrigation requirements, allowing extension providers to generate site-specific rather than generic recommendations (Gupta & Pal, 2025; Sai Satish *et al.*, 2025) ^[22, 48]. Precision agriculture decision-support tools that integrate weather, soil and crop-growth models have been used to optimise irrigation scheduling and input application, reducing costs while improving resource-use efficiency (Narendar *et al.*, 2026; Delgoda *et al.*, 2016) ^[34, 13].

4.4 The Internet of Things and Sensor Networks

IoT-enabled sensor networks provide continuous, real-time data on soil moisture, temperature, humidity and livestock health, feeding automated advisory and decision-support systems and reducing the reliance on periodic manual field assessment (Friha *et al.*, 2021; Subeesh & Mehta, 2021) ^[17, 55]. Applications extend to livestock monitoring through wearable biosensors (Alipio & Villena, 2023) ^[4] and to automated irrigation control informed by weather forecasts and crop-water models (Delgoda *et al.*, 2016) ^[13], with IoT increasingly forming the sensing layer that supplies data to higher-level AI and blockchain systems (Friha *et al.*, 2021) ^[17].

4.5 Blockchain-Enabled Data and Supply-Chain Systems

Blockchain technology is being explored primarily for its capacity to ensure transparent, tamper-resistant record-keeping across agricultural supply chains, supporting traceability, quality assurance and trust between smallholder producers and downstream buyers (Pal & Kant, 2019; Rehman *et al.*, 2023) ^[39, 43]. Empirical feasibility assessments in African food supply chains and broader technical surveys of blockchain-IoT applications in agriculture and livestock management corroborate this traceability potential while highlighting significant implementation barriers (Tang *et al.*, 2024; Yang *et al.*, 2025) ^[56, 58]. Combined with IoT sensing, blockchain has been proposed as a mechanism for secure agricultural data management and for underpinning climate-smart agriculture information systems, although its application within extension and advisory services specifically remains at an early, largely pilot stage (Safeer *et al.*, 2024; Dey & Shekhawat, 2021) ^[47, 14].

4.6 Artificial Intelligence and Generative Chatbot-Based Advisory

The most recent and rapidly advancing frontier of digital extension involves artificial intelligence, machine learning and, since 2023, large language model (LLM)-based generative AI chatbots capable of providing personalized, conversational advisory responses in local languages (Neeraja *et al.*, 2026; Roy *et al.*, 2026; High *et al.*, 2026) ^[37, 46, 24]. Systems such as Digital Green's Farmer. Chat combine curated, government-vetted agronomic knowledge bases with LLM-driven natural-language interfaces, allowing farmers to pose open-ended questions and receive contextually tailored responses regarding crop selection, pest management and input use (High *et al.*, 2026; Feyisa, 2020) ^[24, 16]. Machine-learning-based crop disease diagnosis using image recognition, AI-driven yield prediction and NLP-based advisory chatbots are increasingly piloted in India and sub-Saharan Africa, although evidence on their reliability, farmer trust and impact at scale remains preliminary (Neeraja *et al.*, 2026; Kaushik *et al.*, 2025; Deji *et al.*, 2023) ^[37, 25, 12]. A summary of the principal digital technology categories, representative tools and their extension applications is presented in Table 2.

Table 2. Principal digital technology categories reshaping agricultural extension and advisory delivery

Technology Category	Representative Tools/Platforms	Primary Extension Application	Key source(s)
Mobile advisory (voice/SMS/IVR)	Kisan Call Centre; farmer hotlines; SMS weather alerts	Query resolution, weather and price alerts	(Gouroubera <i>et al.</i> , 2025; Oumer, 2025; Khan <i>et al.</i> , 2020) ^[20, 38, 26]
E-portals and mobile apps	Farmers' Portal; Kisan Suvidha; agri-advisory apps	Integrated advisory, market linkage, scheme info	(Adesiji <i>et al.</i> , 2024; Mane <i>et al.</i> , 2023; Sen <i>et al.</i> , 2024) ^[2, 29, 49]
Remote sensing and precision agriculture	Satellite/drone imagery, GIS decision tools	Site-specific crop and irrigation advisory	(Gupta & Pal, 2025; Delgoda <i>et al.</i> , 2016) ^[22, 13]
Internet of Things (IoT)	Soil/weather sensors, wearable livestock biosensors	Real-time monitoring and automated triggers	(Alipio & Villena, 2023; Friha <i>et al.</i> , 2021; Subeesh & Mehta, 2021) ^[4, 17, 55]
Blockchain-enabled systems	Traceability and secure data-management platforms	Supply-chain transparency and data integrity	(Safeer <i>et al.</i> , 2024; Tang <i>et al.</i> , 2024; Yang <i>et al.</i> , 2025) ^[47, 56, 58]
AI/ML and generative chatbots	Farmer. Chat; NLP crop-advisory bots; disease diagnosis models	Personalized conversational advisory at scale	(Neeraja <i>et al.</i> , 2026; Roy <i>et al.</i> , 2026; High <i>et al.</i> , 2026) ^[37, 46, 24]

5. Opportunities Presented by Digital Extension

Digital technologies present several substantive opportunities for revitalizing agricultural extension. The most fundamental is scale: mobile- and internet-based advisory services can, in principle, reach millions of farmers simultaneously at a fraction of the marginal cost of face-to-

face contact, overcoming the extension-worker-to-farmer ratio constraint that has historically limited coverage (Gouroubera *et al.*, 2025; Ndimbo *et al.*, 2025) ^[20, 36]. Because digital channels are not bound to a fixed visitation schedule, they also enable near real-time delivery of time-sensitive information such as pest and disease alerts,

weather warnings and market price movements, allowing farmers to act promptly on emerging risks and opportunities (Yegbemey & Egah, 2021; Gouroubera *et al.*, 2023) ^[59, 21].

Second, digital tools enable a degree of personalization that generic, campaign-style extension messaging cannot easily achieve. AI-driven advisory systems can tailor recommendations to a farmer's specific location, crop, farm size and even growth stage, moving advisory delivery away from blanket recommendations toward genuinely site-specific guidance (High *et al.*, 2026; Yegbemey & Egah, 2021) ^[24, 59]. Third, digital platforms facilitate two-way and farmer-to-farmer communication, supporting peer learning, feedback loops and co-innovation in ways that traditional one-way broadcast and even T&V-style visits could not readily support (Khan *et al.*, 2025; Mulungu *et al.*, 2025) ^[27, 31].

Fourth, digital extension can improve resilience and continuity of service delivery during crises that restrict physical movement, as demonstrated during the COVID-19 pandemic, when extension systems worldwide pivoted to mobile applications, radio and virtual engagement to sustain farmer contact (Singh *et al.*, 2025; Hassoun *et al.*, 2023) ^[53, 23]. Fifth, when deliberately designed with gender-responsive features-including content in local languages, household-level rather than individual targeting, and involvement of women in application design-digital extension has shown potential to narrow, rather than widen, gender gaps in access to agricultural information (Ragetlie *et al.*, 2022; Mutuku *et al.*, 2026) ^[41, 33].

Sixth, integration of digital advisory with market information and mobile financial services can strengthen farmers' bargaining position and reduce dependence on intermediaries, as illustrated by platforms combining agronomic advice with real-time price discovery and access to credit (Narendar *et al.*, 2025; Singh, 2015) ^[35, 52]. Finally, evidence from India and East Africa suggests that digitally enabled advisory services, when combined with quality data and localization, are associated with measurable gains in yield, input-use efficiency and market prices received by participating farmers, underscoring the economic case for continued investment in digital extension infrastructure (Gouroubera *et al.*, 2025; Zheng & Ma, 2023; Giulivi *et al.*, 2023) ^[20, 60, 19].

6. Challenges and Constraints

The opportunities associated with digital extension are counterbalanced by substantial and, in some respects, intensifying challenges. The most widely documented is the rural digital divide: many smallholder farmers, particularly in remote and underdeveloped regions, continue to lack reliable access to smartphones, mobile internet and stable electricity, constraining their ability to benefit from digital advisory platforms regardless of the sophistication of the underlying technology (Ragetlie *et al.*, 2022; Sen *et al.*, 2025) ^[41, 50]. This divide is not merely infrastructural but socio-economic, correlating strongly with income, education and landholding size, so that digital extension risks disproportionately benefiting farmers who are already comparatively well resourced (Ahad *et al.*, 2024; Sen *et al.*, 2025) ^[3, 50].

A closely related and persistent constraint is the gender digital divide. Women farmers frequently report lower rates of mobile phone and smartphone ownership, more limited decision-making autonomy over shared household devices,

and lower levels of digital literacy than men, all of which constrain their independent access to digital advisory content even where household-level connectivity exists (Ragetlie *et al.*, 2022; Mutuku *et al.*, 2026; Ahad *et al.*, 2024) ^[41, 33, 3]. Addressing this divide requires extension systems to move beyond gender-neutral design toward deliberately gender-responsive digital tools and delivery strategies (Ragetlie *et al.*, 2022) ^[41].

Digital literacy constitutes a further constraint that extends beyond farmers to extension personnel themselves. Studies from multiple regions report that the competencies of agricultural extension agents in using digital technologies remain uneven, undermining efforts to integrate digital tools into routine advisory practice and highlighting the need for sustained investment in extension-agent training (Deji *et al.*, 2023; Angello, 2015) ^[12, 7]. Content-related challenges are similarly significant: much digital advisory content has historically relied on generic recommendations poorly adapted to local languages, dialects, cropping systems and farming contexts, reducing perceived relevance and trust among target users (High *et al.*, 2026; Sen *et al.*, 2025) ^[24, 50].

Data governance and privacy present emerging concerns as digital platforms increasingly collect farm-level, financial and even biometric data, raising questions about data ownership, consent, and the potential for commercial exploitation of farmer data by private technology providers without adequate regulatory oversight (Abate *et al.*, 2023) ^[1]. The reliability and timeliness of information delivered through digital channels have also been questioned; assessments of established platforms such as Kisan Call Centres have found persistent gaps in the accuracy, currency and consistency of advisory content, despite generally high farmer satisfaction with accessibility (Tran *et al.*, 2021) ^[57]. Furthermore, behavioural and trust-related barriers-including skepticism toward AI-generated recommendations, preference for known human intermediaries, and limited farmer engagement with feedback mechanisms embedded in chatbot platforms-continue to constrain the effectiveness of even well-resourced digital advisory pilots (High *et al.*, 2026) ^[24]. Finally, the sustainability of many digital extension initiatives remains uncertain beyond initial donor- or project-funded pilot phases, echoing the recurrent-cost problems that historically undermined the Training and Visit system, and underscoring the need for viable long-term financing and institutional ownership models (Rokvić & Vaško, 2016; Pandey *et al.*, 2025) ^[45, 40].

7. Institutional Readiness and Policy Framework

Realising the potential of digital extension depends heavily on the readiness of public extension institutions, the coherence of national policy frameworks, and the extent to which digitalization is embedded within, rather than layered on top of, existing advisory structures. Institutional readiness encompasses several dimensions: the digital competency of extension personnel, the availability of interoperable data systems, the existence of quality-assured and regularly updated agronomic content, and organizational cultures that reward innovation and farmer-centred service delivery (Regan, 2021; Deji *et al.*, 2023) ^[42, 12]. Assessments of publicly funded agricultural research and extension systems indicate that formal recognition of digital advisory work, together with dedicated funding streams and

monitoring mechanisms, remains uneven across countries, constraining the translation of pilot successes into sustained institutional practice (Regan, 2021) ^[42].

Public-private partnerships (PPPs) have emerged as a central institutional mechanism for scaling digital extension, combining the technical and financial capacity of private technology providers, agribusinesses and telecommunications companies with the legitimacy, reach and agronomic knowledge base of public extension systems (Pandey *et al.*, 2025; Moreddu, 2016) ^[40, 30]. Comparative evidence from multiple countries indicates that PPPs bundling technology transfer, market linkage and capacity-building components consistently outperform single-component interventions, though their success depends on clear role differentiation among partners, transparent governance arrangements, and equitable benefit-sharing mechanisms (Pandey *et al.*, 2025; Aseete *et al.*, 2023) ^[40, 8]. Effective PPP design further requires standardised legal and contractual frameworks and extension-specific curricula capable of preparing personnel to operate within pluralistic, multi-stakeholder advisory ecosystems (Pandey *et al.*, 2025) ^[40].

At the policy level, national digital agriculture strategies—such as India's National Mission on Agricultural Extension and Technology and its more recent Digital Agriculture Mission, alongside similar frameworks emerging in parts of sub-Saharan Africa and Southeast Asia—seek to provide overarching direction for infrastructure investment, data governance and the harmonization of fragmented, often donor-driven digital pilots (Pandey *et al.*, 2025; Regan, 2021) ^[40, 42]. However, policy frameworks in many countries continue to lag behind technological deployment, with regulatory gaps particularly evident in relation to farmer data protection, quality assurance of AI-generated advisory content, interoperability standards across competing platforms, and mechanisms for accrediting private digital advisory providers operating within otherwise public extension mandates (Abate *et al.*, 2023) ^[1].

Institutional readiness also requires explicit attention to rural infrastructure investment—electricity, broadband and mobile network coverage—as a precondition for the equitable functioning of any digital extension strategy, together with sustained public commitment to strengthening human capital and digital literacy among both farmers and extension personnel (Ragetlie *et al.*, 2022; Sen *et al.*, 2025) ^[41, 50]. Monitoring and evaluation systems capable of tracking not only the reach but the quality, relevance and equity of digital advisory delivery are similarly identified as a critical, and frequently underdeveloped, component of institutional readiness (Sen *et al.*, 2025; Deji *et al.*, 2023) ^[50, 12].

8. Case Studies and Comparative Analysis

A comparative examination of digital extension initiatives across countries illustrates both the transformative potential and the persistent limitations of digitalisation in practice.

India offers one of the most extensively documented experiences, spanning nearly two decades of digital extension innovation. The Kisan Call Centre, launched in January 2004, provides farmers with toll-free, local-language telephone access to agricultural experts and remains among the largest publicly operated digital advisory services in the world; evaluations report generally high farmer satisfaction with accessibility, although concerns persist regarding the accuracy and timeliness of advice delivered (Oumer, 2025; Singh, 2015; Tran *et al.*, 2021) ^[38, 52, 57]. The privately operated e-Choupal network, established by ITC Limited in 2000, combined internet-enabled village kiosks with market-linkage and input-supply services, and has since evolved into a mobile-first platform integrating artificial intelligence and IoT-based agronomic advisory, illustrating a private-sector pathway to digital extension scaling, albeit one that has drawn scrutiny regarding uneven geographic coverage and dependence on a single corporate actor (Singh, 2015) ^[52].

In sub-Saharan Africa, mobile-based advisory services have been extensively piloted and evaluated, with meta-analytic evidence indicating generally positive, though heterogeneous, effects on technology adoption across multiple countries (Gouroubera *et al.*, 2025; Muromba *et al.*, 2025) ^[20, 32]. Ethiopia's national farmer hotline demonstrates the potential of low-bandwidth, voice-based advisory services to reach farmers with limited smartphone access, though uptake remains constrained by low digital literacy and infrastructural gaps (Oumer, 2025) ^[38]. Ghana's post-pandemic e-extension experience highlights both the accelerated adoption of ICT-based advisory channels during COVID-19 and the continuing need to integrate digital strategies with existing extension methods to ensure inclusive reach, particularly for marginalised communities (Siankwilimba *et al.*, 2023) ^[51]. Gender-focused digital extension interventions, such as a household-targeted programme in Tunisia that engaged husband-and-wife farmer pairs, provide encouraging evidence that deliberately gender-responsive design can narrow, rather than reproduce, gender gaps in digital advisory access (Ragetlie *et al.*, 2022) ^[41].

Emerging generative AI-based advisory platforms, including Digital Green's Farmer.Chat, deployed in partnership with national agriculture ministries in East Africa and piloted in South Asia, represent the newest generation of digital extension and combine curated, government-vetted knowledge bases with conversational large language model interfaces capable of responding to open-ended farmer queries in local languages (High *et al.*, 2026; Feyisa, 2020) ^[24, 16]. Early evidence suggests strong potential for scaling personalised advisory delivery, though systematic evaluation of yield, income and behavioural impacts remains limited, and challenges relating to content accuracy, farmer trust and feedback-loop engagement persist (High *et al.*, 2026) ^[24]. A comparative summary of these initiatives is presented in Table 3.

Table 3: Comparative summary of selected digital agricultural extension initiatives

Initiative / Country	Technology Type	Key Strength	Key Limitation	Source
Kisan Call Centre, India	Voice-based call centre (IVR/human agent)	Wide reach; toll-free, local-language access	Variable accuracy and timeliness of advice	(Oumer, 2025; Singh, 2015; Tran <i>et al.</i> , 2021) ^[38, 52, 57]
e-Choupal, India	Internet kiosks / mobile app (private sector)	Integrated market linkage and input supply	Uneven coverage; single-firm dependence	(Singh, 2015) ^[52]
Farmer's Hotline, Ethiopia	Mobile voice advisory (short-code dial-in)	Low-bandwidth accessibility	Low uptake; limited digital literacy	(Oumer, 2025) ^[38]
Gender-responsive digital extension, Tunisia	SMS, radio and phone-based advisory	Narrowed gender gap via household targeting	Resource-intensive to design and monitor	(Ragetlie <i>et al.</i> , 2022) ^[41]
Farmer. Chat (Digital Green), East Africa/South Asia	Generative AI / LLM chatbot	Personalised, conversational, scalable advisory	Limited impact evaluation; trust and feedback gaps	(High <i>et al.</i> , 2026; Feyisa, 2020) ^[24, 16]
Mobile advisory services, sub-Saharan Africa (multi-country)	SMS/IVR mobile advisory	Positive, scalable effects on technology adoption	Heterogeneous impact on yield/profitability	(Gouroubera <i>et al.</i> , 2025) ^[20]

Taken together, these cases suggest a consistent pattern: digital extension initiatives achieve their greatest impact where they are deliberately layered onto, rather than substituted for, existing human extension capacity, where content is localised and quality-assured, and where deployment is accompanied by explicit attention to gender and digital-literacy gaps. Purely technology-led interventions that neglect these design and institutional dimensions tend to demonstrate more limited or inconsistent impact, reinforcing the case for hybrid, human-plus-digital extension models rather than wholesale digital substitution (Steinke *et al.*, 2021; Sen *et al.*, 2025; Sen *et al.*, 2024) ^[54, 50, 49].

9. Future Research Directions

Several priority areas warrant further research attention as digital extension systems mature. First, rigorous, longer-term impact evaluations-particularly randomised and quasi-experimental studies tracking yield, income, resilience and empowerment outcomes rather than adoption or usage metrics alone-remain scarce relative to the proliferation of digital extension pilots, and are needed to establish a credible evidence base for scaling decisions (Zheng & Ma, 2023; Giulivi *et al.*, 2023) ^[60, 19]. Second, research is needed on the design and evaluation of generative AI and large language model-based advisory systems specifically within smallholder contexts, including their accuracy, bias, explainability, and the mechanisms through which farmer trust in AI-generated recommendations is built or eroded over time (Neeraja *et al.*, 2026; High *et al.*, 2026) ^[37, 24].

Third, further work is required on gender- and equity-sensitive design of digital extension platforms, including how household dynamics, intra-household device sharing, and social norms mediate women's and youth's actual use of nominally available digital tools, moving beyond access metrics toward a deeper understanding of effective use and empowerment (Mutuku *et al.*, 2026; Ahad *et al.*, 2024) ^[33, 3]. Fourth, comparative institutional research on public-private partnership governance models-examining risk-sharing, data ownership, accountability and long-term financial sustainability-would help clarify which partnership configurations are best suited to different country contexts and extension mandates (Pandey *et al.*, 2025; Aseete *et al.*, 2023) ^[40, 8].

Fifth, the integration of IoT, remote sensing and blockchain technologies into mainstream extension advisory workflows, as opposed to isolated technical pilots, remains underexplored, particularly regarding the interoperability of

these data streams with the knowledge bases underpinning farmer-facing advisory chatbots (Safeer *et al.*, 2024; Friha *et al.*, 2021; Dey & Shekhawat, 2021) ^[47, 17, 14]. Sixth, research on data governance frameworks appropriate to agricultural extension contexts-covering farmer consent, data portability and protection against exploitative commercial use of farm-level data-is needed to keep pace with the rapid expansion of data-intensive digital advisory platforms (Abate *et al.*, 2023) ^[1]. Finally, systematic research on the digital competencies, incentive structures and career pathways of extension personnel operating within increasingly hybrid human-digital advisory systems would help ensure that the human extension workforce is strengthened, rather than displaced, by digitalisation (Angello, 2015; Deji *et al.*, 2023) ^[7, 12].

10. Conclusion

Agricultural extension has evolved from a conventional top-down technology transfer approach to a more participatory and digitally enabled advisory system. While traditional extension has played a vital role in improving agricultural productivity, its effectiveness has been constrained by inadequate extension personnel, limited financial resources, weak research-extension linkages, and challenges in reaching diverse farming communities. Recent advances in digital technologies including mobile applications, web-based platforms, remote sensing, the Internet of Things (IoT), blockchain, and artificial intelligence (AI) have significantly expanded the capacity of extension systems to deliver timely, location-specific, and personalized advisory services. Evidence reviewed in this study indicates that these technologies have improved farmers' access to information, enhanced technology adoption, and strengthened agricultural decision-making across many regions. Despite these opportunities, several challenges continue to hinder the widespread adoption of digital extension. Persistent digital divides, gender disparities, inadequate infrastructure, limited digital literacy, concerns regarding data privacy and governance, and the long-term sustainability of digital initiatives remain significant barriers. The effectiveness of digital extension therefore depends not only on technological innovation but also on supportive policies, institutional capacity, trained extension professionals, and effective public-private partnerships.

Overall, the evidence suggests that the future of agricultural extension lies in hybrid advisory systems that integrate the scalability and efficiency of digital technologies with the contextual knowledge, trust, and interpersonal support

provided by human extension agents. Future research should emphasize rigorous impact evaluation, inclusive digital innovation, ethical AI applications, and stronger institutional frameworks to ensure that digital transformation contributes to equitable, resilient, and sustainable agricultural development. Such an integrated approach will be essential for delivering effective extension services capable of addressing the evolving challenges of global agriculture.

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