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Digital Agriculture and Extension: A Review of ICTs, Mobile Applications, AI, IoT, and Decision-Support Tools for Sustainable Farming

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Abstract

Transfer of technology is rapidly evolving from traditional, top-down, face-to-face methods where experts directly instruct farmers toward integrated, digitally enabled, multi-channel advisory systems. Digital technologies including mobile applications, SMS advisories, IoT sensors, AI-driven analytics, and decision-support systems (DSS) offer unprecedented opportunities to enhance outreach, deliver personalized recommendations, strengthen farmer decision-making, and improve resource-use efficiency. These tools can facilitate two-way communication, integrating local knowledge and feedback into extension services, while also supporting market linkages, climate risk management, and sustainability goals. Evidence indicates that mobile and SMS-based advisories are highly inclusive and scalable, whereas IoT, AI, and DSS represent advanced precision technologies with adoption challenges due to costs, digital literacy, connectivity, and institutional capacity. While digital extension can increase productivity, incomes, and resilience, it also risks reinforcing existing inequalities and creating dependencies if accessibility, local relevance, trust, and human facilitation are insufficiently addressed. Key barriers include digital literacy gaps, content localization, gender and socio-economic inequities, data governance, and institutional limitations. Successful digital agriculture requires blended extension models, participatory content design, capacity-building, inclusive service and financing mechanisms, and robust policy frameworks. This review synthesizes recent empirical and market evidence on digital agriculture adoption, impacts on knowledge, productivity, and market access, and identifies research gaps and best practices for inclusive, sustainable, and scalable digital extension services.

***Key words*:** Digital communication, Sustainable farming, ICTs, Mobile applications, Artificial intelligence, Decision-support tools

Agricultural extension is undergoing a profound transformation, shifting from conventional, face-to-face, top-down approaches to integrated, multi-channel advisory systems in which digital technologies play a pivotal role. The transformation of agricultural extension from conventional, face-to-face, top-down approaches to digitally enabled, multi-channel advisory systems reflects both a major opportunity and a set of new risks for farming communities, especially smallholders [1]. On the one hand, digital technologies ranging from mobile phones and interactive platforms to IoT-based advisories offer unprecedented possibilities for scaling outreach, delivering timely and personalized recommendations, lowering transaction costs, and strengthening farmer decision-making. These tools can also facilitate two-way communication, allowing farmers to share local knowledge and feedback, thus addressing some of the limitations of one-directional, expert-driven extension. On the other hand, this digital shift risks reinforcing the digital divide: farmers with limited literacy, digital skills, connectivity, or financial resources may be excluded from the benefits, thereby exacerbating existing socio-economic inequalities [2]. Moreover, overreliance on technology without adequate institutional support, localized content, and human facilitation can reduce trust and adoption, particularly in rural and marginalized communities. Thus, while digital extension systems promise to make agriculture more efficient, inclusive, and sustainable, their success critically depends on ensuring equitable access, farmer capacity-building, participatory content design, and supportive policies, without which the transformation may reproduce the very gaps it seeks to overcome.

Digital agriculture encompasses a broad spectrum of innovations, ranging from farm-level sensors and Internet of Things (IoT) devices to mobile applications, SMS-based advisories, artificial intelligence (AI) driven analytics, and decision-support systems (DSS) that translate complex datasets into actionable recommendations [3]. These tools increasingly support farmers in making critical decisions related to crop planning, pest and disease management, irrigation scheduling, and market engagement. Digital agriculture integrates multiple

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technologies, each offering distinct advantages while catering to different levels of farming needs and capacities [4]. Farm-level sensors and IoT devices provide highly granular, real-time data on soil, water, and crop conditions, enabling precise input use and improved productivity; however, their adoption by smallholders is often constrained by high upfront costs and the need for reliable connectivity and maintenance [5]. By contrast, mobile applications and SMS-based advisories are far more accessible, requiring only basic phones and literacy, and are thus highly effective in disseminating timely weather alerts, pest warnings, and crop management tips to large numbers of farmers at relatively low cost [6]. At a more advanced level, AI-driven analytics harness big data from satellite imagery to climate models to generate predictive insights, such as early warnings of pest outbreaks or yield forecasts, which can significantly enhance risk management; yet, these systems demand robust digital infrastructure and institutional mediation to ensure that outputs are farmer-friendly and locally relevant [7]. Similarly, decision-support systems (DSS) translate complex datasets into context-specific recommendations, offering farmers tailored guidance on crop planning, irrigation scheduling, and marketing, though their utility depends heavily on farmer training and the adaptability of models to diverse agro-ecological conditions. In sum, while mobile and SMS-based platforms represent the most inclusive entry point for smallholders, IoT, AI, and DSS embody the next frontier of precision and sustainability, requiring public–private partnerships, subsidies, and capacity-building to ensure their equitable adoption [8].

The adoption of digital technologies in agricultural extension offers significant potential benefits, but these gains must be assessed alongside risks of dependence and exclusion. On the positive side, digital platforms enhance timeliness and precision, allowing farmers to receive localized and real-time information on weather, pests, and markets, while personalized, context-specific recommendations improve decision-making beyond the one-size-fits-all model of traditional extension [9]. Reduced transaction and information costs, combined with the ability to extend advisory services to remote or underserved regions, position digital agriculture as a powerful tool for inclusivity and efficiency. Yet, an over-reliance on such technologies risks creating new vulnerabilities: farmers may become dependent on platforms that are subject to connectivity failures, data biases, or private-sector control of information flows. Moreover, without adequate digital literacy, infrastructure, and trust-building mechanisms, these tools may reinforce inequalities by privileging farmers who are already better resourced, while marginalizing smallholders with limited access [10]. Thus, while digital extension systems promise to broaden access and transform advisory services, their sustainability depends on balanced integration with traditional knowledge systems, institutional oversight, and safeguards against technological exclusion. By enhancing resource-use efficiency, tools such as IoT-based irrigation systems and precision input applications help farmers optimize water, fertilizer, and pesticide use, reducing waste and environmental degradation while lowering production costs. The resulting improvements in farm productivity arise not only from higher yields but also from better crop quality and reduced losses through timely interventions informed by data-driven insights [11]. At the same time, digital platforms strengthen market linkages by connecting farmers directly with buyers, price information, and e-commerce platforms, thereby shortening value chains, improving transparency, and increasing farm incomes. Perhaps most critically, these innovations bolster resilience to climate variability by integrating early warning systems, predictive analytics, and adaptive management strategies, enabling farmers to anticipate and mitigate risks associated with droughts, floods, or pest outbreaks. However, realizing these sustainability benefits requires ensuring equitable access, localized content, and institutional support, since the absence of these conditions could lead to uneven adoption, exclusion of marginalized farmers, or even over-dependence on external platforms. In essence, digital agriculture, when inclusively deployed, has the potential to act as both a productivity driver and a resilience mechanism, making it a cornerstone of sustainable farming systems [12].

While digital tools offer immense potential for improving farm decision-making, their benefits hinge on farmer access to affordable technologies, as high costs of devices, connectivity, and maintenance often exclude smallholders [13]. Even when access is possible, the lack of adequate digital skills can hinder effective use, highlighting the importance of literacy, training, and capacity-building. Equally vital is the provision of locally relevant content generic or poorly localized advisories may fail to align with farmers' specific agro-ecological and socio-economic contexts, undermining trust and adoption [14]. Beyond the farmer level, the success of digital agriculture rests on institutional frameworks and supportive policy environments, which can facilitate public-private partnerships, ensure data governance, and promote equitable access. Absent these supports, digital initiatives risk creating a digital divide, where well-resourced farmers reap disproportionate benefits while marginalized groups are left behind, thereby reinforcing inequalities in agricultural systems [15]. Thus, the statement underscores that technology alone is insufficient; its transformative power depends on embedding digital agriculture within inclusive, context-sensitive, and institutionally backed ecosystems.

In this review, recent market insights and empirical evidence to examine the role of ICTs, mobile platforms, AI, IoT, and DSS in agricultural extension. Particular attention is given to quantifying emerging trends, assessing impacts on farmer decision-making and livelihoods, and identifying the institutional and infrastructural prerequisites for scaling digital agriculture in a sustainable and inclusive manner.

Methods (search and selection)

This review employed a narrative/systematic hybrid approach, combining the structured rigor of systematic reviews with the contextual flexibility of narrative synthesis. The search strategy prioritized recent and high-quality sources, focusing on peer-reviewed journal articles published between 2018 and 2025, complemented by authoritative market and sector reports as well as documented program case studies to capture practical insights and policy relevance. Searches were conducted across major academic databases (e.g., Scopus, Web of Science, Google Scholar) and institutional or industry repositories. A predefined set of search terms was applied, including "digital agriculture," "mobile advisory," "AI in agriculture," "IoT agriculture," "decision support systems agriculture," "mKisan," and "eNAM", ensuring coverage of both global frameworks and region-specific initiatives. Inclusion criteria emphasized sources that provided empirical evidence, quantitative data, or detailed program documentation, while exclusion criteria filtered out opinion pieces and non-validated reports. Representative, high-quality sources were selected to substantiate key arguments, and numerical claims were supported by empirical or market-based evidence wherever possible. The final body of literature integrates academic, institutional, and applied perspectives, with all primary sources cited in the reference list.

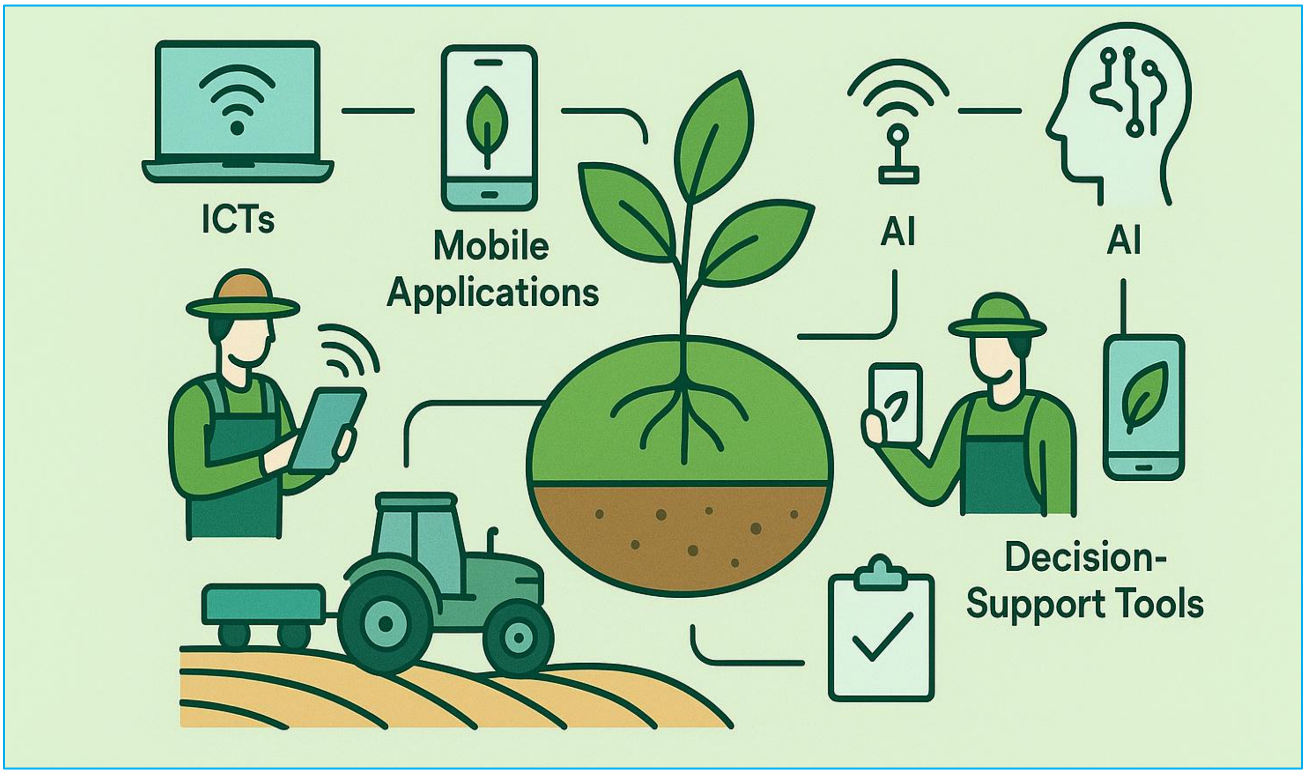

Fig 1 Digital agriculture and extension for sustainable farming

Market and adoption trends (quantitative snapshot)

Digital agriculture market size

Recent estimates consistently show that the digital agriculture market is substantial and expanding rapidly, though figures vary depending on methodology, scope, and base year. Global Market Insights valued the sector at ≈ USD 22 billion in 2023, while Markets and Markets reported USD 24.2 billion in 2024, and Allied Market Research placed it at USD 18.6 billion in 2023; despite these differences, most forecasts converge on double-digit growth (≈10-11% CAGR) over the next decade, projecting the market to reach USD 50-60 billion by 2032-2034 [16]. Variations arise because some reports adopt narrow definitions (focusing on IoT and precision farming hardware/software) while others use broader scopes that include advisory platforms, digital marketplaces, and financial services. Despite definitional differences, the evidence strongly indicates that digital agriculture has transitioned from a niche sector into a major global industry, driven by rising adoption of IoT, AI analytics, mobile advisories, and decision-support tools, with Asia-Pacific often identified as the fastest-growing region [17].

AI in agriculture

The AI in agriculture market is rapidly expanding, with 2023-2024 estimates ranging between USD 1.9 and 4.7 billion, depending on the source, and forecasts projecting exceptionally high compound annual growth rates (≈20-26%) over the next decade. This strong trajectory reflects surging investment and adoption of AI applications such as crop health monitoring, predictive analytics for yield and pest management, precision irrigation, and farm automation, which enhance decision-making and efficiency at multiple stages of production. The wide variation in reported values arises from differing market definitions some focusing narrowly on AI-driven farm management tools, others including robotics, drones, and integrated digital platforms but all reports converge on the conclusion that AI represents one of the most transformative and fast-growing segments of digital agriculture [18-20].

IoT device proliferation

Global IoT device adoption is accelerating, with an estimated 16.6 billion connected devices in 2023 projected to reach ≈18.8 billion in 2024, according to IoT Analytics, forming a critical foundation for sensor-based precision agriculture. This rapid proliferation underpins the deployment of farm-level technologies such as soil moisture probes, climate sensors, GPS-enabled machinery, and livestock trackers, enabling real-time data collection and more precise, resource-efficient farming practices [21]. While these figures capture all IoT sectors, their growth highlights the expanding digital infrastructure on which agriculture increasingly relies, positioning IoT as a backbone technology for smart farming ecosystems.

Smartphone and farmer digital behaviour (India example)

In India, smartphone adoption and low mobile data costs have significantly accelerated farmers' engagement with digital platforms, driving uptake of mobile-based advisory services, digital payments, and online agri-market transactions [22]. Reports, including those by McKinsey & Company, highlight rising smartphone penetration among rural households and growing comfort with digital tools, which are reshaping farmer behavior from information access to purchasing and selling decisions. This shift not only expands the reach of agricultural extension but also signals a broader digital transformation of rural economies, where mobile devices serve as the primary gateway to advisory, financial, and market services [23].

National digital platforms (India)

India's National Agriculture Market (eNAM) exemplifies the institutional push toward digitalization of agri-markets, providing a unified electronic trading platform that integrates physical mandis to improve transparency, price discovery, and farmer access to wider markets. Since its launch in 2016, eNAM has expanded progressively, now linking more than 1,300 mandis across 20+ states and union territories, with millions of farmers and traders registered, and dashboards offering real-time statistics on trade volumes, commodities, and price trends [24]. By digitizing mandi operations, eNAM reduces intermediaries, standardizes transactions, and enhances market efficiency, though challenges remain in terms of adoption disparities across regions, digital literacy, and infrastructure gaps. Overall, eNAM represents a landmark institutional intervention in India's agricultural digital ecosystem, laying the groundwork for more inclusive and data-driven agri-markets.

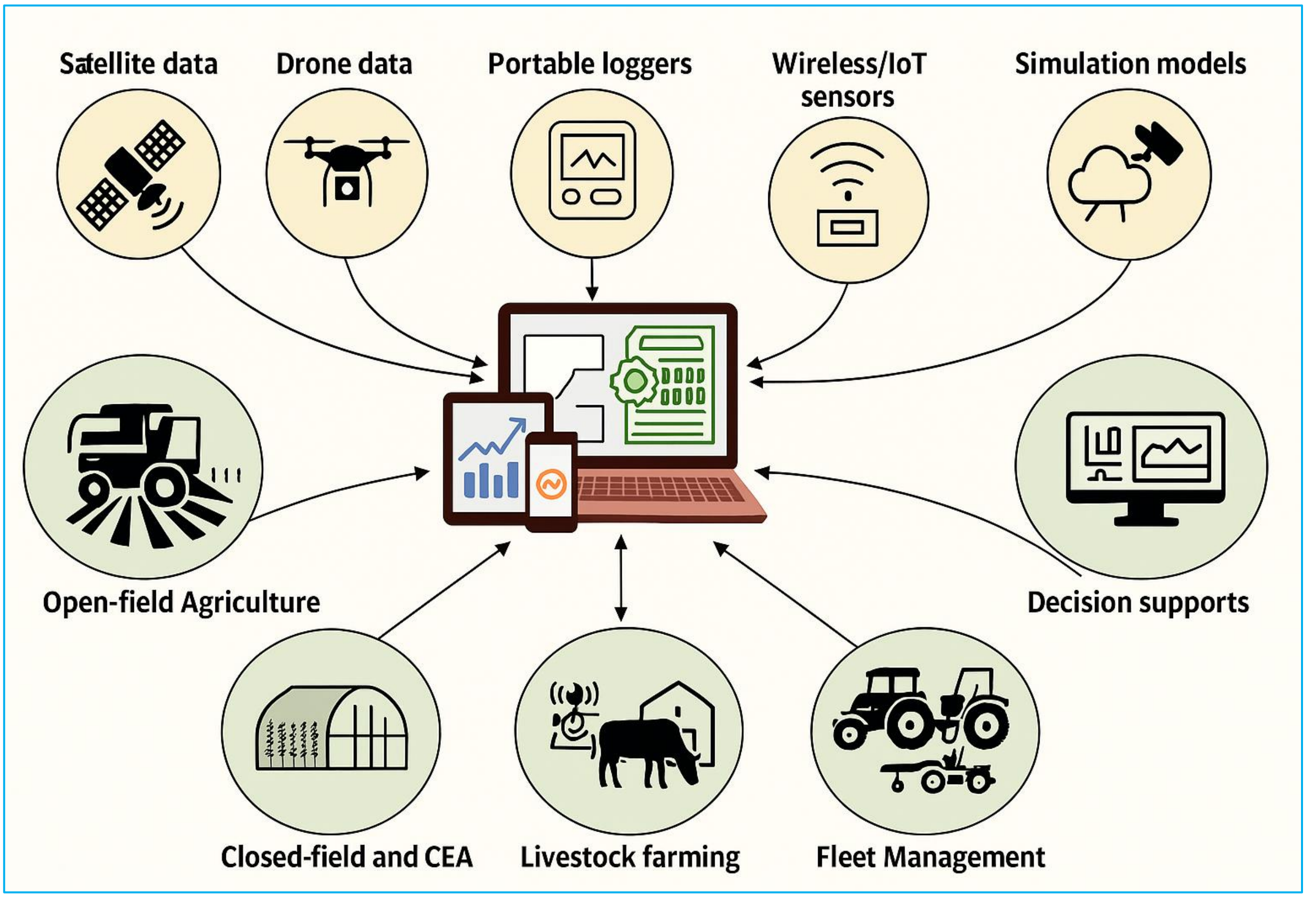

Fig 2 Data-driven smart farming ecosystems integrate multi-source inputs with digital decision-making platforms to improve agricultural efficiency, sustainability, and productivity

Technologies and their roles in extension

ICTs and mobile applications

Technologies play a pivotal role in agricultural extension by bridging information gaps and enabling timely access to knowledge, with ICTs and mobile applications emerging as the most influential tools in recent years. Mobile phones through voice calls, SMS, smartphone apps, and interactive voice response (IVR) systems have become the dominant digital channel for delivering agro-advisories, particularly in low- and middle-income countries where extension resources are limited [25]. These platforms provide farmers with crucial services such as weather-based forecasts, pest and weed management alerts, and context-specific agronomic recommendations, often delivered through both government-led and private initiatives. Empirical evidence indicates that mobile apps and SMS-based advisories enhance farmers' knowledge and promote adoption of improved practices, though their effects on yields and incomes remain mixed, largely contingent on the quality, relevance, and design of the content delivery [26]. Notably, a recent open-access study from India highlighted that agricultural mobile applications demonstrated strong usability attributes and were well-received by farmers, reinforcing their potential as scalable, farmer-friendly tools for strengthening agricultural extension.

Strengths

One of the key strengths of digital extension technologies, particularly ICTs and mobile applications, lies in their ability to deliver information at a very low marginal cost once the system is developed, allowing service providers to reach vast numbers of farmers across geographically dispersed regions without the need for frequent physical interactions. Unlike traditional face-to-face extension methods that are resource-intensive, mobile and digital platforms enable asynchronous delivery, meaning farmers can access messages, advisories, and learning materials at their own convenience rather than being bound to scheduled meetings or visits. This flexibility is particularly important for smallholders who balance farming with multiple livelihood activities and may not always be available during conventional extension sessions. Furthermore, these platforms support multimedia formats such as images, infographics, short videos, and audio clips that make complex agricultural practices easier to understand, especially for farmers with low literacy levels, thereby enhancing learning and adoption [27]. Together, these strengths make digital extension a scalable, cost-effective, and inclusive approach for modern agricultural advisory services.

Limitations

Despite their promise, digital extension tools face several limitations that constrain their effectiveness and inclusiveness. Literacy and language barriers remain significant challenges, as many farmers especially women, older populations, and marginalized groups struggle to engage with text-heavy advisories delivered via SMS or mobile apps, particularly when content is not provided in local dialects. Low levels of digital literacy and limited familiarity with smartphones further restrict the ability of some groups to fully utilize available applications, leading to uneven adoption across socio-economic categories [28]. Moreover, many agro-advisory apps and ICT platforms still offer largely generic recommendations that fail to adequately capture local agro-ecological conditions, crop varieties, and farming practices, resulting in advice that is less actionable or relevant for individual farmers. The lack of localized, context-specific content often reduces trust and sustained use of these services, underscoring the need for better customization, user-centered design, and integration of farmer feedback in digital extension systems [29].

AI (Machine learning, computer vision, predictive analytics)

Artificial Intelligence (AI), encompassing machine learning, computer vision, and predictive analytics, is increasingly transforming agricultural extension by enabling more precise, timely, and scalable advisory services [30]. AI-driven tools have been effectively applied in areas such as pest and disease diagnosis through image classification, yield forecasting using predictive models, and optimization of input use for improved efficiency and sustainability [31]. Platforms like Plant Village and virtual agronomist applications allow farmers to capture images of affected crops and instantly receive accurate pest or disease identification along with tailored recommendations, thereby compensating for the scarcity of field-level agronomists. Field reports and media coverage highlight successful applications in smallholder contexts, such as Kenyan farmers using AI-based tools to enhance crop management and increase yields, underscoring the potential of these technologies to improve productivity and resilience in resource-constrained systems [32-33]. However, while promising, the evidence base remains largely anecdotal, with rigorous randomized controlled trials (RCTs) and systematic evaluations still limited, highlighting the need for more empirical research to validate long-term impacts and scalability.

IoT and sensors

Soil moisture probes, weather stations, and automated irrigation controllers support precision irrigation and nutrient management. The growing number of connected devices (global IoT growth) enables denser monitoring networks but cost and maintenance remain obstacles for smallholder uptake without service models. The Internet of Things (IoT) and sensor-based technologies are playing a transformative role in modern agricultural extension by enabling real-time data collection and precision management of farm resources [34]. Devices such as soil moisture probes, automated weather stations, and smart irrigation controllers provide farmers with site-specific insights that help optimize water use, improve nutrient management, and enhance overall productivity while conserving scarce resources. The global expansion of IoT networks has increased the availability and affordability of connected devices, allowing for denser monitoring systems that can generate more granular and accurate data to inform decision-making at both farm and regional levels [35]. However, despite their potential, the adoption of IoT tools among smallholders remains limited due to high upfront costs, technical complexity, and ongoing maintenance requirements, which are often beyond the capacity of resource-constrained farmers. As a result, the widespread integration of IoT in smallholder systems will likely depend on the development of innovative service delivery models, such as subscription-based or cooperative approaches, that can lower barriers to access and ensure sustainability

Decision-support systems (DSS)

DSS combine data (weather, soil, crop models) and algorithms to generate management recommendations (when to irrigate, fertilizer rates, pest thresholds). Recent research emphasizes human-centred DSS that integrate farmer preferences, economics, and water quality goals. Adoption depends on perceived usefulness, transparency of recommendations, and integration with extension workflows.

Decision-support systems (DSS) are increasingly recognized as powerful tools in agricultural extension, as they integrate diverse datasets including weather forecasts, soil parameters, and crop growth models with algorithms to generate actionable recommendations on key management decisions such as optimal irrigation scheduling, fertilizer application rates, and pest or disease intervention thresholds [36]. Beyond purely technical outputs, recent research emphasizes the importance of developing human-centred DSS that account for farmer preferences, socio-economic constraints, and broader sustainability goals such as water quality protection, thereby enhancing relevance and trust. Successful adoption of these systems is shaped not only by the accuracy of their recommendations but also by farmers' perceptions of their usefulness, the transparency and explainability of the underlying decision logic, and how well they are embedded within existing extension services and advisory workflows. By combining scientific rigor with user-centred design, DSS hold significant potential to improve farm-level decision-making, though their scalability depends on effective training, capacity-building, and institutional support

Evidence on impact (what works, where)

Knowledge and advisory reach

Multiple evaluations report that mobile advisories and apps increase farmers' access to information and may change knowledge and short-term practices (e.g., pesticide timing, planting decisions). Examples include state-level evaluations of mKisan and other mobile advisory pilots. Evidence on the impact of digital extension highlights that mobile advisories and agricultural apps have significantly expanded the reach of knowledge and advisory services, particularly in contexts where traditional extension coverage is limited [37]. Multiple evaluations demonstrate that these tools improve farmers' access to timely, relevant information and often influence short-term decision-making, such as adjusting pesticide application timing, adopting recommended planting dates, or responding proactively to weather advisories. For instance, state-level assessments of India's mKisan initiative and various mobile advisory pilot programs have shown measurable improvements in farmer awareness and adoption of recommended practices, underscoring the value of ICTs in bridging information gaps at scale [38]. However, while evidence on knowledge gains and short-term behavior changes is robust, studies also suggest that translating these improvements into consistent yield gains or higher farm incomes is less straightforward, as outcomes depend heavily on the quality of advice, contextual relevance, and farmers' ability to act on the recommendations.

Yield and income impacts

Evidence is mixed isolated case stories and some program evaluations report yield increases (notably where advice is precise, timely, and actionable), but systematic evidence at scale is still developing. Meta-analyses and high-quality impact evaluations are fewer relative to the number of deployments. Evidence on yield and income impacts of digital extension tools remains mixed, with a growing but still limited body of rigorous research. While isolated success stories and select program evaluations document significant yield gains particularly in cases where advisories are precise, timely, and tailored to local conditions such outcomes are not consistently observed across all contexts [39]. For example, some mobile-based interventions have reported notable increases in productivity and farmer incomes when advice directly addressed critical decisions such as fertilizer application timing or pest management. However, systematic evidence at scale is still emerging, and meta-analyses as well as high-quality randomized controlled trials remain relatively scarce compared to the rapid proliferation of digital advisory deployments. This imbalance highlights a gap between the enthusiasm for scaling digital solutions and the availability of robust empirical validation of their long-term effects on productivity and livelihoods, underscoring the need for more comprehensive evaluations [40].

Market linkages

Platforms digitizing markets (e.g., eNAM in India) have improved price transparency and market access for some farmers, though challenges in logistics and on-ground adoption limit uniform benefits. Digital platforms that focus on market linkages, such as India's electronic National Agriculture Market (eNAM), have shown promise in improving price transparency and expanding market access for farmers by reducing information asymmetries and enabling more competitive bidding [41]. By providing real-time price data and connecting buyers and sellers across regions, these platforms aim to reduce farmers' dependence on local intermediaries and enhance their bargaining power. Early evidence suggests that some farmers have benefited through better price discovery and access to wider markets, contributing to potentially higher incomes. However, the impact remains uneven, as logistical challenges such as transportation, storage, and grading facilities, along with varying levels of digital literacy and trust in online platforms, continue to constrain adoption. Furthermore, many smallholders still rely on traditional market channels due to limited awareness or difficulties in navigating digital systems, indicating that while eNAM and similar initiatives hold transformative potential, their success ultimately depends on strengthening physical infrastructure, farmer training, and integration with on-ground extension support [42].

Success stories and program examples

mKisan and mobile advisory programs (India)

Longstanding national and state programs delivering SMS/voice advisories; multiple state evaluations show increased information access though varying degrees of behavioral change. Success stories from large-scale digital advisory initiatives illustrate both the potential and challenges of ICT-enabled extension, with India's mKisan platform serving as a prominent example. Launched as a nationwide system, mKisan delivers SMS and voice-based advisories in regional languages, providing millions of farmers with timely information on weather forecasts, pest and disease alerts, and crop management practices [43]. Complemented by various state-level mobile advisory programs, these services have been instrumental in broadening farmers' access to agricultural knowledge at scale, especially in regions where traditional extension coverage is limited. Evaluations conducted in multiple states indicate that while such platforms have substantially improved the reach and timeliness of information, the degree of behavioral change such as adoption of recommended practices varies widely across farmer groups. Factors such as literacy, digital skills, local relevance of content, and the ability to act on recommendations influence outcomes. Nonetheless, mKisan and related initiatives are frequently cited as successful models of ICT in agriculture, demonstrating how government-backed digital systems can institutionalize advisory delivery and reach millions of smallholders cost-effectively [44].

eNAM (India)

A national electronic trading platform linking mandis; dashboards and government reporting show progressive scaling of mandis onto the platform, improving digital market infrastructure. India's electronic National Agriculture Market (eNAM) exemplifies a large-scale digital intervention aimed at modernizing agricultural marketing and enhancing market access for farmers. As a national electronic trading platform linking numerous mandis across states, eNAM provides a centralized system for price discovery, online bidding, and transaction tracking, thereby improving transparency and efficiency in agricultural trade [45]. Government dashboards and reporting indicate progressive scaling, with an increasing number of mandis being integrated onto the platform, which has strengthened the underlying digital market infrastructure. By facilitating smoother interactions between buyers and sellers and reducing reliance on intermediaries, eNAM holds the potential to improve farmers' bargaining power and income opportunities. However, while the platform demonstrates notable progress in digitizing market operations, the benefits are influenced by complementary factors such as logistics, warehousing, and farmer familiarity with digital systems, underscoring the need for continued capacity-building and infrastructure support to fully realize its transformative potential.

AI tools for smallholders

AI-driven tools are increasingly being leveraged to support smallholder farmers across a range of agricultural activities, with platforms providing image-based crop diagnosis, pest and disease identification, and tailored management recommendations. Utilizing machine learning and computer vision, these systems allow farmers to capture images of their crops and receive near-instant guidance on pest control, nutrient management, and other agronomic practices, effectively extending the reach of scarce expert agronomists [46-47]. Reports and journalistic accounts indicate that farmers using these AI applications have reported improvements not only in pest and disease management but also in broader aspects of crop management, including yield optimization, irrigation scheduling, and input use efficiency. These tools enhance farmers' decision-making, increase confidence in technology adoption, and contribute to more informed, timely interventions on the farm, although rigorous empirical studies on long-term impacts and scalability are still limited, highlighting an area for further research and evaluation [48].

National digital agriculture strategies

Countries such as India are actively developing national digital agriculture strategies aimed at transforming the agricultural sector through technology-driven interventions. These multi-year plans focus on creating comprehensive agricultural big data platforms that integrate information on weather, soil health, crop performance, and market trends, enabling data-driven decision-making at scale. Complementing these platforms, digital planting frameworks are being introduced to guide farmers on optimal sowing times, crop selection, and resource allocation, with the objective of improving productivity, efficiency, and climate resilience [49].

By institutionalizing digital infrastructure and fostering interoperability between various ICT tools, these strategies seek to enhance the reach and effectiveness of advisory services, support precision agriculture, and facilitate evidence-based policy planning. Such coordinated national approaches demonstrate the potential of digital agriculture to systematically strengthen farm-level decision-making while addressing broader goals of food security and sustainable development [50].

Barriers and challenges

Digital divide and inclusion

Even with rising smartphone ownership, many farmers particularly women, the elderly, and the lowest-income households face barriers: limited digital literacy, local language content scarcity, gendered access to devices, and affordability constraints. Several analyses indicate only a minority of farmers in some regions feel comfortable using digital tools without assistance.

The persistence of the digital divide in agriculture highlights that rising smartphone penetration alone does not guarantee equitable participation in digital ecosystems, as many farmers especially women, the elderly, and low-income households continue to face significant barriers such as limited digital literacy, lack of localized and user-friendly content, gender-based disparities in device ownership, and affordability challenges [51]. Evidence from multiple studies shows that while smartphones and mobile internet have become more accessible, only a minority of farmers in several regions feel confident in independently using digital platforms for agricultural transactions, advisories, or market access, often requiring assistance from family members or intermediaries [52]. This uneven capacity to engage with technology underscores the importance of inclusive strategies that prioritize digital literacy training, the development of context-specific applications in local languages, and policies aimed at reducing the structural inequities that limit access for marginalized groups, thereby ensuring that digital transformation in agriculture is not only widespread but also inclusive [53].

Content relevance and localization

Generic advice delivered digitally may be irrelevant if not localized for agro-ecology, crop variety, or resource constraints. Co-design with farmers and integration of indigenous knowledge are important for uptake. A key challenge in the effectiveness of digital agricultural interventions lies in the relevance and localization of content, as generic advisories or standardized messages often fail to address the diverse agro-ecological conditions, crop varieties, and resource constraints faced by farmers across regions [54]. Without tailoring recommendations to local soils, climate variability, input availability, and farming practices, digital tools risk low adoption and limited impact on productivity or sustainability. Research emphasizes the importance of co-designing solutions with farmers, ensuring participatory approaches that reflect ground realities, and integrating indigenous knowledge systems that farmers already rely on for decision-making. Such localization not only enhances trust and usability but also bridges the gap between modern scientific advisories and traditional practices, creating hybrid knowledge systems more likely to be adopted at scale [55].

Trust, verification, and risk

Farmers may distrust algorithmic recommendations without transparent causal explanations or local validation. Risk-averse farmers need demonstration of reliability before changing practices. Trust, verification, and risk perception play a critical role in the adoption of digital agricultural tools, as farmers often remain skeptical of algorithmic recommendations that lack transparent causal explanations or locally validated evidence [56]. Given the high stakes associated with agricultural decision-making where a single misstep can threaten livelihoods-risk-averse farmers are hesitant to alter established practices without clear proof of reliability. Studies indicate that farmers are more likely to adopt digital advisories when they are reinforced through trusted intermediaries, peer networks, or field demonstrations that provide tangible evidence of outcomes under local conditions [57]. Building credibility thus requires not only technological accuracy but also mechanisms for verification, participatory validation, and trust-building, ensuring that digital innovations are perceived as dependable and relevant before farmers are willing to integrate them into their production systems [58].

Institutional and capacity constraints

Extension agencies may lack staff trained to interpret data outputs or to integrate digital advisories into extension workflows. Maintenance and service models for IoT devices and sensors are often absent for smallholders [59]. Institutional and capacity constraints significantly limit the scalability and effectiveness of digital agriculture, as many extension agencies struggle with inadequate staffing, limited digital skills, and insufficient training to interpret complex data outputs or seamlessly integrate digital advisories into existing extension workflows [60]. This gap weakens the potential of digital tools to complement traditional extension, as frontline workers may lack both the technical expertise and institutional support needed to translate digital insights into actionable farmer guidance. Moreover, the absence of sustainable maintenance and service models for IoT devices, sensors, and other hardware creates further barriers for smallholders, who often cannot afford ongoing repairs or replacements [61]. Evidence suggests that without robust institutional capacity-building, long-term financing, and locally accessible service ecosystems, digital agriculture risks remaining fragmented and unevenly adopted, rather than becoming a transformative force for smallholder farming systems [62].

Data governance, privacy, and equity

Data ownership and privacy issues, and the risk of commercial capture of farmer data without fair benefits, are rising concerns as platforms scale (Policy frameworks are nascent in many countries). Data governance, privacy, and equity have emerged as pressing concerns in the expansion of digital agriculture, as the rapid scaling of platforms raises unresolved questions about data ownership, consent, and the fair distribution of benefits derived from farmer-generated information [63]. Farmers often lack clarity on how their data ranging from land records and crop practices to market transactions is collected, stored, and shared, creating vulnerabilities to commercial capture where private firms may monetize insights without ensuring reciprocal value for producers [64]. This imbalance risks exacerbating existing inequalities by concentrating informational and economic power in the hands of technology providers while leaving smallholders with limited bargaining capacity. In many countries, policy frameworks and regulatory safeguards remain nascent, with weak enforcement mechanisms around privacy, data portability, and equitable access [65]. Addressing these governance gaps is critical for building trust, protecting farmer rights, and ensuring that data-driven innovation in agriculture advances inclusivity rather than reinforcing structural inequities

Research gaps and priorities

Rigorous impact evaluations at scale

More randomized controlled trials (RCTs) and longitudinal studies are needed to move beyond case stories and to measure sustained productivity, income, and welfare effects across contexts. Research on digital agriculture continues to be constrained by significant evidence gaps, particularly the lack of rigorous impact evaluations conducted at scale, which limits the ability to generalize findings across diverse agro-ecological and socio-economic contexts [66]. While numerous pilot projects and case studies suggest positive outcomes in productivity, market access, or information flow, few have been tested through randomized controlled trials (RCTs) or longitudinal designs capable of measuring sustained impacts on farmer income, resilience, and welfare over time. This reliance on short-term or anecdotal evidence hinders robust policy formulation and investment decisions, as scalability and long-term effectiveness remain uncertain. Future research priorities must therefore emphasize systematic, comparative, and context-sensitive evaluations that account for heterogeneity in farmer capacities, institutional environments, and technology ecosystems, enabling a clearer understanding of what works, for whom, and under what conditions [67].

Human-centred DSS design research

Understanding how to integrate farmer preferences, risk attitudes, and labour constraints into DSS recommendations. Human-centred decision support system (DSS) design research is increasingly recognized as essential for ensuring that digital tools align with the realities and priorities of farmers, rather than imposing top-down prescriptions that may be impractical or poorly adopted. Effective DSS must move beyond purely agronomic optimization to incorporate farmer preferences, household risk attitudes, and labour availability, acknowledging that agricultural decision-making is shaped as much by socio-economic constraints and livelihood strategies as by technical recommendations [68]. By integrating participatory approaches, behavioural insights, and localized knowledge into system design, researchers can develop DSS that provide actionable, context-relevant guidance farmers are more likely to trust and adopt. Such an approach bridges the gap between algorithmic efficiency and human decision-making complexity, ultimately enhancing usability, adoption, and long-term impact of digital advisory systems [69].

Inclusion strategies

Evidence on effective ways to close gender and socioeconomic digital divides in adoption of agritech. Inclusion strategies in digital agriculture focus on addressing the structural barriers that disproportionately affect women, marginalized groups, and low-income farmers in accessing and benefiting from agritech, with emerging evidence highlighting several effective approaches [70]. Gender-sensitive interventions, such as targeted digital literacy training for women, improving affordability of devices through subsidies or shared-access models, and designing interfaces in local languages with intuitive features, have been shown to enhance participation. Community-based delivery models, including digital hubs, farmer producer organizations, and women's self-help groups, also play a critical role in diffusing technology more equitably [71]. Moreover, embedding social norms awareness and participatory co-design processes ensures that digital tools are responsive to the specific constraints faced by disadvantaged groups, rather than reinforcing existing inequalities. Scaling such inclusive practices, supported by enabling policies and public–private partnerships, is vital for ensuring that the digital transformation of agriculture translates into broad-based and equitable development outcomes [72].

Business/service models for smallholders

Viable maintenance, financing, and value-sharing models for sensor networks and AI services. Developing viable business and service models for smallholders is critical to ensure the sustainability and scalability of sensor networks, AI-driven advisory services, and other advanced agritech solutions, which often face challenges of high upfront costs, maintenance burdens, and uneven value capture [73]. Evidence suggests that models built around shared infrastructure such as cooperative ownership, subscription-based services, or pay-per-use arrangements can make technology more affordable while distributing risks and benefits across farmer groups. Equally important are financing mechanisms, including microcredit, bundled insurance, and public-private partnerships, that lower entry barriers for resource-constrained farmers. Value-sharing frameworks, where benefits from data insights or productivity gains are equitably distributed among farmers, service providers, and technology developers, are also essential to build trust and long-term engagement [74]. Without such inclusive and adaptive models, digital innovations risk remaining accessible only to larger or wealthier farmers, whereas well-designed business and service ecosystems can democratize access and ensure sustained impact for smallholders [75].

Data governance frameworks

Comparative policy work and normative guidelines for fair data practices in agriculture. Data governance frameworks in agriculture are increasingly recognized as essential for ensuring fair, transparent, and equitable data practices, particularly as digital platforms and precision technologies generate vast amounts of farmer-level information [76]. Comparative policy analyses highlight significant variation across countries, with some advancing comprehensive guidelines on data ownership, consent, portability, and benefit-sharing, while others remain at early stages of regulatory development. Normative frameworks emphasize the need for farmer-centric principles that safeguard privacy, prevent exploitative data capture, and guarantee that farmers retain agency over how their data is used and monetized [77]. Establishing common standards and interoperable policies across jurisdictions is critical for building trust, facilitating cross-border collaboration, and ensuring that digital agriculture evolves in ways that empower rather than marginalize smallholders. Ultimately, effective governance requires a balance between enabling innovation and protecting farmer rights, supported by participatory policymaking and multi-stakeholder engagement to create equitable data ecosystems in agriculture [78].

Practical recommendations for extension practitioners and policy makers

Adopt blended extension models

Combine digital channels (SMS, apps, AI diagnostics) with community-level facilitation (lead farmers, FFS, local extension agents) to translate information into practice. Practical recommendations for extension practitioners and policymakers emphasize the adoption of blended extension models that integrate digital technologies with community-based facilitation to enhance the relevance, accessibility, and adoption of agricultural advisories [79-80]. Digital channels such as SMS alerts, mobile applications, and AI-driven diagnostic tools-can rapidly disseminate information on best practices, weather forecasts, pest management, and market opportunities, reaching farmers at scale. However, evidence indicates that digital advisories are most effective when complemented by on-the-ground support through lead farmers, farmer field schools (FFS), and local extension agents who can contextualize recommendations, demonstrate practical implementation, and build trust among risk-averse or digitally inexperienced farmers [81]. This hybrid approach leverages the efficiency and scalability of digital tools while addressing the limitations of technology adoption, ensuring that knowledge is not only accessible but actionable, thereby enhancing productivity, resilience, and overall impact on rural livelihoods [82].

Localize content and languages

Invest in agro-ecological tailoring and regional language multimedia (audio, video) to reach low-literacy users. Localizing digital agricultural content and supporting multiple regional languages is critical for ensuring that advisory services are accessible and actionable, particularly for low-literacy farmers who may struggle with text-based or generic recommendations [83]. Tailoring content to specific agro-ecological conditions such as soil types, climate variability, and prevalent crop varieties enhances the relevance and applicability of guidance, while multimedia formats, including audio, video, and interactive visual aids, facilitate comprehension and engagement among diverse user groups. Research highlights that investments in localized, context-sensitive, and linguistically inclusive materials significantly improve adoption rates, empower marginalized farmers, and bridge gaps in digital literacy. By combining agro-ecological specificity with culturally and linguistically appropriate delivery methods, extension services and digital platforms can ensure that technology-driven interventions are both inclusive and impactful, fostering more equitable participation in the digital transformation of agriculture [84].

Build digital literacy programs

Training for farmers (and specifically women farmers) to increase comfort with tools and address the digital divide. Building digital literacy programs is fundamental to bridging the digital divide in agriculture and ensuring that farmers can effectively engage with technology-enabled advisory services, market platforms, and precision tools [85]. Targeted training initiatives enhance farmers' confidence and competence in using smartphones, apps, and online resources, while addressing barriers related to low familiarity with digital interfaces, cybersecurity concerns, and navigation of complex data. Evidence underscores the importance of designing these programs with attention to gender, as women farmers often face additional constraints, including limited access to devices, social norms, and lower prior exposure to digital tools [86]. By incorporating hands-on practice, peer learning, and culturally sensitive instructional materials, digital literacy programs not only empower farmers to independently access relevant information but also promote more equitable participation in agritech adoption, ultimately increasing productivity, resilience, and income opportunities [87].

Ensure transparency and farmer agency

Design DSS and AI outputs that include explanations, uncertainty bounds, and options rather than prescriptive commands. Ensuring transparency and farmer agency in digital agriculture is critical for fostering trust and promoting informed decision-making, particularly when deploying decision support systems (DSS) and AI-driven advisories [88]. Systems that merely provide prescriptive commands risk alienating farmers, especially those who are risk-averse or have deep contextual knowledge of their local conditions. Research emphasizes designing DSS outputs that include clear explanations of recommendations, highlight uncertainty bounds, and present multiple actionable options, allowing farmers to weigh trade-offs and adapt advice to their specific circumstances. Such transparency not only improves comprehension and confidence in digital tools but also respects farmers' experiential knowledge and decision-making autonomy [89]. By integrating these principles, digital advisories can transition from opaque algorithmic outputs to participatory tools that enhance both usability and adoption, ultimately supporting more resilient and context-sensitive farming practices.

Invest in monitoring and evaluation

Systematically measure impacts (economic, agronomic, social) and feedback findings into design cycles. Investing in systematic monitoring and evaluation is essential for understanding the true impacts of digital agricultural interventions and for informing iterative improvements in design and implementation. Comprehensive monitoring and evaluation frameworks should capture a range of outcomes, including economic indicators such as productivity and income, agronomic metrics like yield stability and input efficiency, and social dimensions such as gender inclusion, knowledge retention, and farmer empowerment [90]. By collecting high-quality data and analyzing both short- and long-term effects, practitioners and policymakers can identify what works, for whom, and under which conditions, enabling evidence-based refinements to tools, content, and service delivery models. Moreover, integrating feedback loops from monitoring and evaluation into design cycles fosters adaptive management, ensures accountability, and enhances the scalability and sustainability of digital agriculture initiatives, ultimately aligning technology deployment with the complex realities of smallholder farming systems.

CONCLUSION

Digital technologies give agricultural extension new tools to reach and advise farmers at scale. Market and connectivity trends suggest continued growth of AI, IoT, and mobile platforms. Yet, technology alone will not solve deep-rooted constraints: issues of access, content relevance, trust, and institutional capacity shape real-world outcomes. The most promising path is a blended, human-centred approach where digital tools amplify not replace community extension, combined with robust evaluation, inclusive design, and sound data governance. the transformation of agricultural extension through digital technologies presents a profound opportunity to enhance productivity, resilience, and inclusivity in farming systems, yet it also introduces new challenges and risks that must be carefully managed. Evidence demonstrates that ICTs, mobile applications, AI, IoT devices, and decision-support systems can significantly improve access to timely, localized, and actionable information, strengthen market linkages, and support precision resource management, thereby contributing to higher yields, cost efficiency, and climate resilience. However, the benefits of digital agriculture are contingent upon equitable access, digital literacy, localized content, participatory design, and robust institutional and policy support. Persistent barriers—including gendered disparities, low literacy, affordability constraints, data governance concerns, and uneven infrastructure—highlight the risk of exacerbating existing socio-economic inequalities if these technologies are deployed without inclusion strategies and capacity-building measures.

Practical interventions such as blended extension models, human-centred DSS, agro-ecologically tailored content in local languages, transparent AI outputs, and systematic monitoring and evaluation are critical to bridging these gaps. Furthermore, sustainable business and service models, coupled with normative data governance frameworks, are essential to ensure long-term adoption, trust, and equitable value sharing among stakeholders. Ultimately, the successful integration of digital tools into agricultural extension requires a holistic, context-sensitive approach that balances technological innovation with human agency, institutional capacity, and social equity, positioning digital agriculture not merely as a set of tools but as a transformative ecosystem for sustainable and inclusive rural development.

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