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Digital agricultural extension for smallholder farmers: Innovations, adoption and impact assessment

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Abstract

Digital agricultural extension is evolving the way agricultural knowledge and services are delivered to small farmers by addressing the constraints of the distance, time, human capital and information availability. Mobile applications, SMS, interactive voice response, social media, participatory video, digital platforms, remote sensing, Internet of Things, artificial intelligence and integrated advisory systems are increasingly enabling timely, location-specific and demand-based information. These are crop production, pest and disease identification, weather and climate prediction, input procurement, market access and financial services. But access to digital technologies does not guarantee sustained uptake or measurable improvements in livelihoods of users. Farmers' participation is modified by their perceived usefulness, affordability, digital and functional literacy, trust, language, gender relations, infrastructure, possession of devices, connectivity, and institutional assistance. This review consolidates the latest advances in digital agricultural extension, focusing on technology-based innovations, adoption behavior, impact on socio-economic and agricultural outcomes, and methodologies to assess impact. It points to ongoing problems of the digital divide, splintered platforms, privacy, poor interoperability, and scant evidence on long-term impacts. The review concludes that inclusive, farmer-centred, and locally adapted digital services, that are integrated with traditional extension, farmer organisations and trusted human intermediaries, are likely to be the most effective way to improve adoption, resilience, productivity and sustainable livelihoods for smallholder farmers.

Keywords: Agricultural advisory services, artificial intelligence, digital extension, impact assessment, information and communication technology, smallholder farmers

Introduction

Smallholder farmers cultivate a mix of crops and livestock and rely on natural resources in a context of capital scarcity, market fragmentation, and escalating climate variability. Variety, planting date, nutrient, irrigation, pest, harvest and marketing decisions are tightly time bound, yet public extension systems often that too few staff, insufficient transport, and weak links to research. Conventional visits are

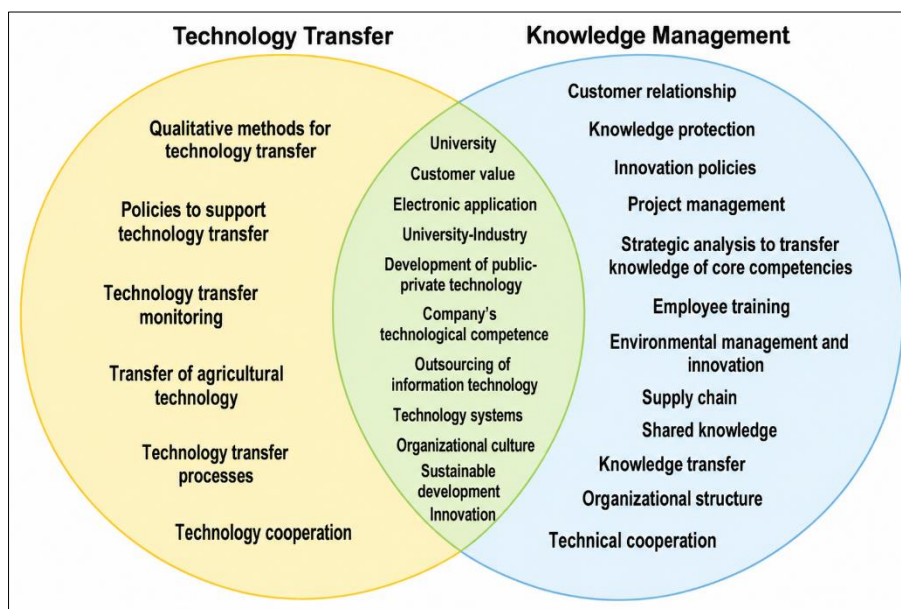
still useful, but they can not replace continuous coverage of the homes. As a result, digital extension has developed as a strategic tool to increase coverage, lower communication costs and deliver faster solutions to location specific problems, while maintaining the type of relationships that credible agricultural knowledge depends (Cole and Fernando, 2021; Rajkhowa and Qaim, 2021) [16, 43]. Digital agricultural extension is the application of digital

communication, data and decision-support technologies to enhance the reach and impact of agricultural extension and advisory services. It combines telephone calls, SMS (short message service), IVR (interactive voice response) with the mobile feedback, videos, social networks, smartphone applications, chatbots, sensors, satellite products and platforms that connect advice with inputs, finance, insurance and markets (Porciello *et al.*, 2022; Singh *et al.*, 2023) ^[41, 48, 50]. The idea is more than just information delivery. Good extension services enable farmers to pose questions, weigh alternatives, add observations, learn together and receive follow-up support. Digitalization therefore changes not only the channel of extension but also its speed, reach, personalization, responsiveness and institutional organization (Klerkx *et al.*, 2019) ^[29].

Interest accelerated during the COVID-19 pandemic, when the isolation exposed the weaknesses of extension approaches that were fully reliant on in-person meetings. Since that time, climate shocks, growing access to mobile phones and improvements in artificial intelligence have further raised the stakes (Baffoe-Bonnie *et al.*, 2021) ^[4]. Evidence reviews, however, warn against technological optimism. Digital services also tend to be adopted first by younger, wealthier, more educated and better connected farmers, while rural communities, women, tenants, elderly farmers, and linguistic minorities remain marginalized. Evaluation should therefore consider who uses a service, whose knowledge informs its recommendations, what decisions are altered, and whether the benefits persist when subsidies or pilot projects are withdrawn (Kansiime *et al.*, 2021) ^[27].

2. From technology transfer to digital knowledge networks: The traditional system of extension delivery was typically a linear line in which researchers developed recommendations, extension agents transferred them, and farmers were supposed to adopt them. Modern extension is more likely to portray farmers as experimenters and knowledge holders within pluralized systems of innovation. Digital tools can serve to support operating models. One-way alerts may better deliver such standardized instructions, while interactive platforms can facilitate diagnosis, feedback, learning among peers, and co-creation. The decisive issue is therefore not whether information is digital but whether the service improves farmers capacity to interpret uncertainty, test recommendations and adapt them responsibly to different soils, crops, labour conditions and household priorities (Fabregas *et al.*, 2019) ^[19].

A beneficial effect pathway starts from reliable availability and continues along exposure, understanding, trust, testing, adoption, correct use and measurable impacts. Disruptions can take place in all stages of the process. A message can be received after the relevant farm operation, a farmer can understand advice but not have the cash to act, or adoption can increase yields but not profits because prices fall. Digital tracers can show exposure and engagement, but learning or change in welfare cannot be established by them alone. Evaluation should link up the analysis of platform analytics with observations on farms, farmer narratives and counterfactual material. This layered perspective distinguishes impressive reach statistics from meaningful, equitable and durable agricultural impact (Yuan and Sun, 2024) ^[57].



Source: Barros *et al.*, 2020 ^[5]

3. Major innovations in digital agricultural extension

3.1 Mobile messaging and interactive voice services

Short message service is still relevant as it operates on cheap phones and in low-bandwidth regions. Messages can deliver weather warnings, crop calendars, pest alerts, vaccination reminders, and market prices at a small marginal cost. But the effectiveness of the messages is constrained by strict character limits, literacy levels, and the fact that phones are

shared. Interactive voice response and outbound voice messages address some barriers as farmers can listen in local languages, they can repeat messages, and they can navigate menus. Call centres offer human clarity while the missed-call arrangements cut costs for farmers. The most powerful services tailor messages to the crop stage, location and previous farmer responses, rather than sending everyone the same advice (Sen *et al.*, 2025) ^[46].

Two-way communication enhances the utility of the fundamental mobile channels. Farmers can report symptoms, ask to be called back, or ask diagnostic questions, allowing advisors to make their recommendations more precise. Voice is known to be important for farmers with minimal literacy levels, but a variety of complexities including foreign accents, multilayered menu structures, and low speech recognition accuracy contribute to abandonment at an early stage. A message should be concise enough to be practical but sufficiently detailed not to lead to dangerously oversimplified actions, particularly in the case of pesticides, animal medicines and weather-sensitive operations. Mobile delivery on its own leads to small average improvements, but when combined with demonstrations, training or field support delivery it leads to much larger and more consistent adoption effects (Singh *et al.*, 2023) ^[48, 50].

3.2 Video-mediated and multimedia extension

Participatory video makes technical advice visible through locally familiar situations. Farmers can watch on equipment, crop stages and hand movements that are hard to describe in writing. Community viewing enables facilitators to hold up, reflect, compare experiences and note down questions, and short clips can be distributed later through mobile phones. Videos with local farmers, local dialects, and local conditions in the fields are sometimes more convincing than general lectures given by experts. Their value is not derived solely from audiovisual delivery but from facilitated dialogue and group learning. However, the extension needs to check for agronomic validity, reveal local constraints and revise advice if new varieties, pest resistance, regulations or climate condition changes occur (Abate *et al.*, 2023) ^[1]. Evidence from southern India shows the advantage of layering communication channels. A cluster-randomized intervention for cashew communities paired face-to-face video with brief messages and interactive voice recordings; mobile reinforcement resulted in greater recall, knowledge and adoption of best practice compared with video alone. Related methods assist women and time-poor farmers to review content beyond session times, but access remains mediated by phone ownership and control of the household. Learning sequences are more effective at using multimedia: identify the problem, show a solution, ask questions, test out a bit, come back. Uploading big libraries tends to result in low discovery and limited staying power (Kansiime *et al.*, 2019) ^[26].

3.3 Social media and peer-to-peer networks

WhatsApp, Telegram, Facebook, YouTube and some local platforms have emerged as extension platforms where farmers exchange pictures, voice notes, prices and share field experiences. They enable immediacy, build in-group identity, and facilitate low-cost interaction amongst farmers, extension agents, scientists, dealers and buyers. Image-based diagnosis can reduce the response time and archived discussions become an accessible community memory. But open groups also magnify rumours, commercial promotion and inaccurate mixes of pesticides. Sound moderation is a technical challenge requiring trusted experts, transparent rules, paths for escalation and rapid correction of misinformation. Administrators should ensure members' phone numbers are safeguarded and they should seek

consent prior to the dissemination of identifiable images of farms, location details, or personal stories (Meena *et al.*, 2022) ^[34].

3.4 Smartphone applications and decision-support platforms:

Crop calendars, weather forecasts, nutrient calculators, pest libraries, recordkeeping and market information can all be integrated into one interface of smartphone apps. Registration information enables recommendations to be tailored to crop, location, farm size and production stage. Offline storage, icon based navigation and audio downloads enhance usability in area of poor connectivity. But then again complexity and richness of features based apps are usually hard to keep learning process, drain data and need to be updated frequently. A smaller application focused on one worthwhile decision may be used more regularly than a sprawling platform. Developers should focus on completed actions, repeat use, and decision quality instead of downloads, which often inflate the adoption rate as downloading does not imply that the app has been put to use (Coggins *et al.*, 2022; Li *et al.*, 2022) ^[15, 33].

Decision-support systems translate soil tests, weather, crop models, and farmer observations into suggested actions. They are only as good as the assumptions that are ferried through unrealistic expectations, and appropriate level of local calibration. A fertilizer calculator designed for irrigated commercial fields may not be appropriate for intercropped, rainfed or smallholder farming. Advisories should offer realistic alternatives for decisions to be taken, benefits, costs, risks and at the time when recommendations need to be changed. The farmers need explanations, not prescriptions without explanations. Extension workers are able to explain outputs, identify outliers and report model breakdown. So decision support enhances professional judgment and respects farmer choice rather than algorithms as bulwarks against situation-specific knowledge (Shams *et al.*, 2024) ^[47].

3.5 Artificial intelligence and conversational advisory

Artificial intelligence is broadening digital augmentation with image recognition, speech technologies, predictive analytics and conversational systems (Gholami and Al Abdwani, 2024) ^[21]. A farmer may take a photo of a diseased leaf, dictate symptoms and get a preliminary diagnosis with suggested next steps. Generative agents can translate technical content, summarize local guidance, and even respond to follow-up inquiries at any point. Next-gen conversation agents have proven the potential of multilingual, context-aware interaction at scale, yet the available evidence mainly relates to engagement and response quality rather than impact on long-term livelihoods. Thus, advancing from promising interaction to reliable, cost-effective and scientifically validated agronomic advice remains a core challenge for research (Pacal *et al.*, 2024; High *et al.*, 2026) ^[40, 23].

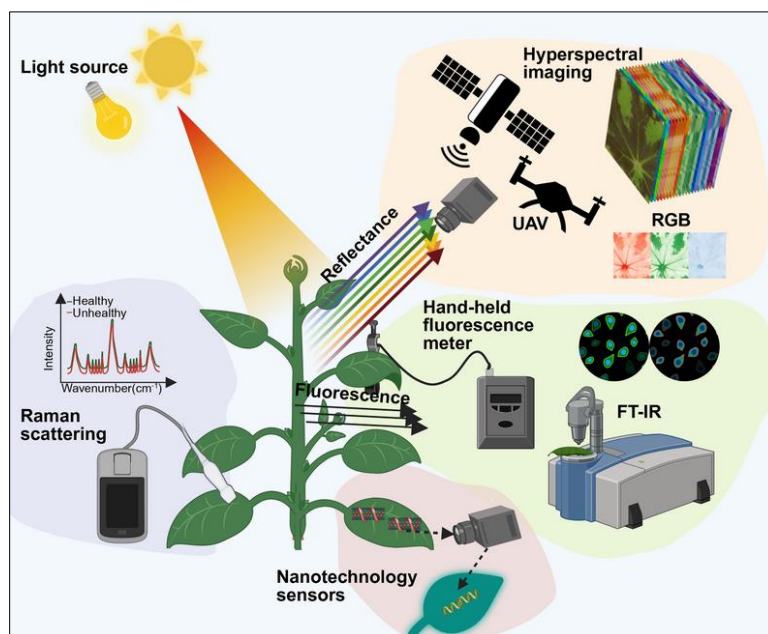
AI should function within a verified knowledge system. Retrieval from sanctioned crop guides, relevant regulations, weather feeds, and market sources is more reliable than free generation from general internet material. High-risk questions are flagged and referred to agronomists, veterinarians, or plant-health laboratories. Systems should have uncertainty statements, source transparency, feedback channels, and ongoing auditing for languages, crops, and user

communities. Voice interfaces have the potential to increase usability, but recognition of low-resource languages is still inconsistent. Models, service systems and operational processes require separate evaluation because accurate laboratory answers may still fail farmers through latency, weak interfaces, outdated knowledge, inappropriate recommendations or absent follow-up support (Jones-Garcia *et al.*, 2026) ^[25].

3.6 Remote sensing, sensors and connected diagnostics

Satellite imagery, drones, automated weather stations, soil-moisture sensors and networked traps could transform extension from broad recommendation to risk-based

targeting. These experts are now able to detect drought stress, late planting, anomalies in vegetation or possible pest outbreaks and they can rank the need for site visits accordingly. Such resources are critical particularly when extension districts are geographically expansive and personnel are limited. They must be resolved and interpreted so as to match small plots that are irregular in shape, intercropped, and where boundaries and crops signals are mixed. Sensor alerts, too, need maintenance, calibration and a responsive pathway. Data that are inaccessible to a cost-effective countermeasure can increase stress and deliver minimal benefit to agronomy (Delfani *et al.*, 2024) ^[17].



Source: Krishnamoorthi *et al.*, 2025 ^[30]

3.7 Digital climate and weather advisory services

Climate services translate forecasts into farm decisions about sowing, irrigation, fertilizer, spraying, harvesting and livestock protection. Raw probability forecasts are almost never good enough. Farm-specific advice on lead time, uncertainty, and alternatives consistent with their resource base are needed. Strategic decisions are informed by seasonal outlooks, tactical decisions are supported by short-range forecasts, and nowcasts alert users to imminent dangers. Rain gauges installed by locals and observations of farmers can make information more relevant and trustworthy. Advice calendars should also take into consideration the crop stage because the impact of a given amount of rainfall or heat event differs across establishment, flowering and harvest. Feedback after each season contributes to the improvement of both predictions and advised courses of action (Nyoni *et al.*, 2024) ^[38].

Research on climate information use tends to focus on preparedness, timeliness of farmers' decision-making and risk aversions, but is context-dependent given the variability of forecast skill and farmers capacity to respond. An accurate warning will not alter behaviour if seed, labour, credit or irrigation is not available. Advice should be integrated with contingency inputs, insurance, water management and local disaster response at services. We need to differentiate

between the receipt of a forecast and the understanding, trust and use of a forecast. Recent field evidence has demonstrated large productivity increases from weather and climate services, highlighting their promise and the need for careful attention to evaluation approaches, variation by crop, and selection into service use (Bizo *et al.*, 2024) ^[8].

3.8 Integrated platforms for markets, finance and services: Digital extension is also increasingly embedded within platforms that package advice with input ordering, digital payments, credit, insurance, mechanization rental, and output marketing. Bundling may overcome a key constraint of information-only interventions: farmers may know what to do but lack inputs, finance, or buyers. Transaction histories might also reduce information asymmetries between borrowers and lenders, and make traceability more robust. But commercial incentives may skew advice towards products from platform partners. Farmers should be clearly informed about sponsorship, be given the freedom to compare options and the independent agronomic advice should be clearly separated from the advertising. Public and cooperative regulation is important when a single platform controls information, transaction, and farmer data (Fielke *et al.*, 2020) ^[20].

4. Understanding adoption and continued use

4.1 Usefulness, simplicity and compatibility

Adoption is a process and not a single decision. Farmers become aware, consider relevance, trial, integrate the service into their routines and subsequently continue, alter, or cease it. Usefulness and ease of use continue to be important, however, agricultural compatibility is just as influential. Advice must be tailored to local crops, calendars, mixed farming systems, labour availability and risk tolerance. Early value should be evident: a proper pest diagnosis, a saved spray, a timely rainfall warning or a better price may build trust. Registration requirements, alien terminology, and lengthy menus contribute to the friction. Thus, designers need to reduce number of steps, remember what users prefer, and offer assistance at the point where confusion is most likely to occur (Vaidya *et al.*, 2023) ^[54].

4.2 Infrastructure and affordability

Network coverage, access to electricity, quality of device and cost of data are the enablers of adoption. Owning a phone at home may be estimated inaccurately by broken phones, poor signal, not enough storage, shared phones and inability to buy data. Applications for continuous broadband are inaccessible to a wide range of their target users. Offline mode, compressed media, free calls, content download and sync on intermittent connectivity enhance robustness. Shared community digital kiosks and devices are also options, but privacy and scheduling issues must be addressed. The cost of ownership, including of the device, charging, repairs, data, subscriptions, and the time required in learning or waiting for answers, should be assessed as a fraction of the varying farm income (Porciello *et al.*, 2022) ^[41].

4.3 Literacy, language and digital capability

The barriers of illiteracy aren't just for reading. Readers have to interpret icons, they have to navigate menus, they have to judge the credibility of sources, they have to manage passwords, they have to understand probabilities, units and digital transactions. Translation does not guarantee understanding as dialect, accent and farming terms vary from place to place. Voice, pictures, demonstrations and conversations help to dismantle barriers, when pilot-tested with real users. Digital fluency is attained through the learning-by-doing pathway, and not by one-off training. Extension agents, rural youth and farmer champions can deliver support close at hand. Training should address misinformation, privacy, fraud and the practical application of advice so farmers gain confidence as decision-makers and not just button-pushers (Chandra *et al.*, 2024) ^[12].

4.4 Trust, relevance and information quality

Farmers evaluate digital information on the basis of past experience, recommendations from peers, reputation of the source, or results they can observe. Trust increases as advice is timely, admits uncertainty, and is grounded in realities of the field. It diminishes sharply after a wrong diagnosis, undisclosed sponsorship, or unanswered complaint. Valid local extension agents can lend legitimacy, but only when they are contacted first by and are comfortable with the service. Systems should enable identification of content authors and sources of evidence with revision dates and provide a transparent path for correction. Advice also needs

to consider constraints on resources: recommendations that are technically best but not affordable or accessible will be seen as irrelevant even to the extent they are scientifically valid (Rohit *et al.*, 2024) ^[44].

4.5 Gender and intersectional inclusion

Women farmers often have less access to phones, data expenditure, time, mobility and training attendance and digital registration can be prone to listing the male head of the household as the farmer. Content can also ignore crops, livestock and postharvest processes that are managed by women. At a minimum, inclusive design involves sex-disaggregated needs assessment, direct recruitment, training at convenient times, voice-based options, women trainers, and safe channels for feedback. Similar considerations apply to older farmers, tenants, landless producers, pastoralists, persons with disabilities and minority-language speakers. Digital tools have the potential to reinforce existing social and economic divides if inclusion is not consciously designed, funded, monitored and evaluated throughout the process (Abdulai *et al.*, 2023) ^[2].

4.6 Institutional readiness and adviser capacity

Extension organizations cannot play digital at the edges such as adding an application within unchanged workflows. Devices, connectivity, digital skills, responsibilities and time are needed by agents to respond. As travel drops, farmer queries can multiply. It is answered questions that erode trust in the absence of triage, escalation, and service levels. Digital platforms would need to be connected with research, plant-health, veterinary, meteorological and market organisation so that multi-dimensional problems are referred to specialized knowledge. Adviser performance metrics need to prioritize the quality of responses, farmer learning and inclusion of diverse perspectives rather than volume of messaging. The learning of the organization is just as critical: persistent farmer queries should inform research focus and training and policy and thereby close the feedback loop between fields and institutions (Khatri *et al.*, 2024) ^[28].

4.7 Business models and sustainability

A lot of digital extension relies on short-term projects, free trials, or content supported by donors. After the money runs out, platforms might start charging users, cut back on moderation, or stop updating recommendations. Smallholders enthusiastically value advisory services, but have limited ability and willingness to pay the full costs, at least before benefits have been proven. Viable models might involve a mixture of public financing for core advice, cooperative membership, business-to-business agreements, transaction charges, and/or well-regulated commercial partnerships. Bundling can cross-subsidize advice, but it also can undermine neutrality. Cost transparency, interoperability, and portability give farmers protection from lock-in. Financial sustainability should not come at the cost of harvesting too much data or favouring particular products (Urdu *et al.*, 2024) ^[54].

5. Evidence of impact on smallholder farmers

5.1 Knowledge, learning and practice adoption

The most uniform effect of digital extension is greater use of information, including recall and technical information. The

impact on practice adoption is generally positive but smaller because doing so requires labour, money, inputs and conviction. High-level evidence syntheses suggest digitally enabled agricultural advice has the potential to increase yields by a modest amount on average and enhance the likelihood of adopting recommended practices. Yet the results differ widely between crops, regions, delivery channels and groups of farmers. Recent meta-analyses report positive average effects from digital information interventions, but emphasize large heterogeneity in study outcomes, quality of implementation, study design and the persistence of measured benefits (Beach *et al.*, 2025) ^[6].

5.2 Productivity, profitability and household welfare

The effects on yields depend on the type of crop, the farmer's prior knowledge, the quality of recommendation and the constraints on production. Tailored advice is likely to be more effective in changing behaviour than generic broadcasts, but more precise targeting entails more costs for data and delivery. Profits can increase through higher yields, better quality, reduced input expenditures or avoided loss, but they can also decrease if advice raises costs without predictable output prices. Therefore, studies should focus on the gross margin and risk, rather than only on the yield. Household welfare results including consumption, dietary diversity, indebtedness and asset building, typically take longer to be observed. Short trials run through one good season cannot demonstrate resilience or long-term poverty alleviation (Fabregas *et al.*, 2019) ^[19].

Evidence needs to be interpreted in light of research design. Recent comparable observational and matching studies sometimes find large productivity gaps between app users and non-app users, but adopters are also more educated, wealthy, have more extension contact and are more motivated. Randomized encouragement, phased rollout, and credible quasi-experimental designs deliver stronger attribution. Even randomized message delivery can be contaminated by non-use and spillovers through farmer networks. Thus the assignment to treatment is different from the exposure to the treatment and the intention-to-treat and the treatment-on-treated estimates are both useful. Transparent reporting of baseline balance, attrition, compliance, and uncertainty is critical before impressive percentages are turned into policy promises (Rajkhowa and Qaim, 2021) ^[43].

5.3 Climate resilience and risk management

Digital extension can improve resilience by allowing farmers to foresee hazards, diversify responses, and recover rapidly. Alerts on the weather, pests and livestock might help farmers avoid losses even if the average size of their crops and herds don't change much. This benefit is not well accounted for by assessments that rely solely on mean production. Related indicators are averted mortality, yield variability, downside risk, timeliness of protective action, recovery time and confidence in contingency planning. Services can also reduce unnecessary spraying or watering. With repeated false

alarms, one gets tired, and a forecast that is confident but wrong can put people more at risk. The resilience effect is on that account a function of forecast performance, quality of communication and availability of practical response options (Burlig *et al.*, 2024) ^[9].

5.4 Market access, finance and bargaining power

Price information can lower search costs and enhance the bargaining power of farmers, especially in cases of market fragmentation. Digital records could enable credit scoring, insurance enrollment and quicker disbursements. But formal inclusion can bring new risks: opaque deductions, fraudulent buyers, digital debt, automated exclusion, and reliance on one platform. The impact on market should be gauged through realized prices, marketing cost, rejected produce, payment delay, sales concentration and farmer command over transactions. Household level analysis is essential as a registered user need not control the income that results. Thus, extension has to integrate market information and financial literacy, contract comprehension, grievance redress mechanisms and collective marketing capacity (Levi *et al.*, 2020) ^[32].

5.5 Social empowerment and institutional change

Digital extension can amplify farmers voices through eliciting questions, complaints, citizen reporting and expert contact. Producer organizations can organize the purchase of inputs, report on local issues, and press for responsive public services. Rural youth could potentially assume new identities as digital intermediaries, drone operators, data collectors, and service entrepreneurs. Such results are relevant even when early yield improvements are small. In contrast, platforms may exert a form of centralized power by establishing what counts as valid knowledge, ranking farmers, or nudging behaviour via non-transparent advice. Impact is to be assessed through changes in agency, confidence, network engagement, ownership of data and influence over service agendas. Empowerment is about having greater meaningful choices and not just about receiving increased messages (Yadav *et al.*, 2026) ^[55].

5.6 Environmental and food-safety outcomes

Guidance on thresholds, weather-based spraying, nutrient balancing, irrigation scheduling and soil cover can help to avoid overuse of inputs and environmental stress. Digital traceability could facilitate food safety and access to differentiated markets. However, environmental gains are frequently extrapolated a priori from recommended practices rather than measured in the field. A decline in pesticide applications can be compensated by higher toxicity, just as improvement in fertilizer use efficiency can co-exist with rising use. Assessments should be conducted for active ingredient, nutrient balances, water use efficiency, soil quality indicators, emission proxies, and adherence to residue standards wherever possible. Recommendations must also be filtered through the lenses of occupational safety, resistance management and off-farm effects (Tambo *et al.*, 2026) ^[52].



6. Impact assessment framework for digital extension

6.1 Begin with a testable theory of change

A rigorous evaluation begins with a clear definition of the farmer problem, the target population, the service components, and the causal pathway. Outputs of inputs like content design, software, and agent training include enrolment, message delivery, and question response. They should lead to outputs like exposure and understanding, intermediate outcomes such as experimenting and practising correctly, and final outcomes like profit, resilience, equity, and environmental performance. Assumptions need to be made explicit: phones are still within reach, advice is timely, inputs are available and markets operate. Considering alternative explanations helps evaluators select indicators and avoid finding no effect because they mistakenly attribute implementation failure to the underlying agronomic recommendation (Glewwe and Todd, 2022) ^[32].

6.2 Measure reach as a quality-adjusted funnel

Reach should be reported as a sequence: eligible population, awareness, registration, successful contact, meaningful engagement, comprehension, repeated use and action. Disaggregation by sex, age, landholding, education, location, phone access, and other contextually relevant variables should be applied at each stage. Counting the sent messages or downloads overestimate the reach when the numbers are inactive or the applications are not opened. Quality-adjusted metrics incorporate timeliness, completion of advisory tasks, successful referral, relevance rated by the farmer and the percentage of recommendations delivered before the decision deadline. Funnel analysis identifies points of attrition of and can help programmes to optimize design prior to waiting for final impact estimates (Mutuku *et al.*, 2026) ^[37].

6.3 Use mixed methods and appropriate counterfactuals

Randomized controlled trials can identify causal effects when services are provided individually, by village or based on phased implementation. Encouragement designs are appropriate designs when access to the intervention cannot be ethically denied but active encouragement can be randomized. Difference-in-differences, regression discontinuity, instrumental variables and matching techniques may enable quasi-experimental analysis of impact

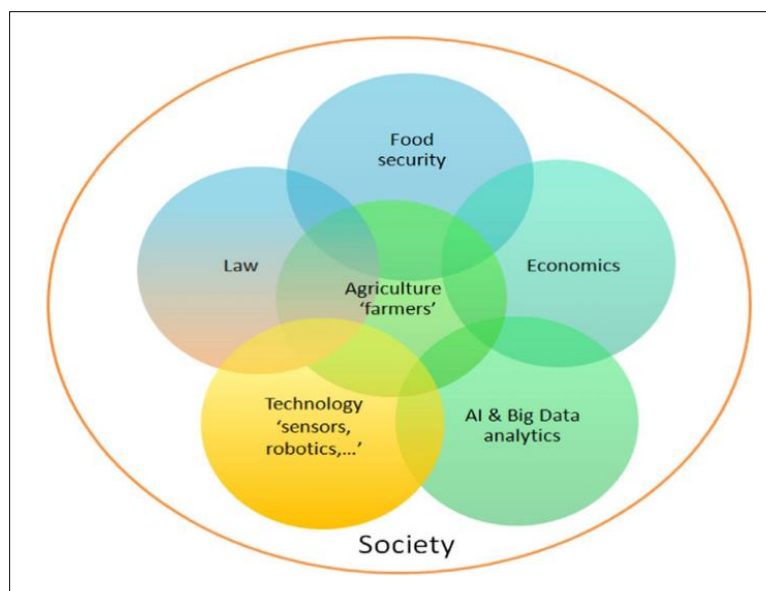
when their assumptions are generated. Quantitative attribution can be complemented by key informant interviews, focus groups, observation and case tracing in order to explain mechanisms, adaptation and unintended effects. No one method is suitable for all questions. Platform usability, in contrast, can be monitored with rapid iterative designs, while income, resilience and institutional change necessitate seasonal or multi-year designs with strong comparison groups (Cattaneo *et al.*, 2024) ^[11].

6.4 Integrate digital analytics with farm-level verification

Server logs at low cost can unconditionally track delivery, open, listen duration, searches, queries and revisit. These data expose patterns of engagement and facilitate adaptive management, but they are ambiguous both technically and behaviorally. High listening times can suggest interest, confusion or a phone that was left on the hook. Shared devices obscure user identity while offline sharing creates unmeasured spillovers. Analytics should be integrated, with consent, with surveys, field measurements, and qualitative evidence. Data minimization is critical: programmes should only collect data that is necessary, establish retention periods, and shield participants from secondary use not related to evaluation or service delivery improvement (Scherr *et al.*, 2026) ^[45].

6.5 Assess cost-effectiveness and scalability

Low marginal costs of messages could be masking significant fixed costs for software, localization, expert validation, farmer support, data protection and ongoing updating. Economic analysis should consider total and incremental costs per farmer reached, engaged, adopting, and benefiting. Cost-effectiveness may be reported in terms of cost per unit of yield gain, income increase, loss averted, or practice adopted, while cost-benefit analysis may test alternative prices, seasons and scale assumptions. Comparisons to standard and blended extension are more informative than comparisons to no service. Other scalability considerations include staff workload, server reliability, content governance, procurement, interoperability, and recurrent budgets, in addition to the technical feasibility to scale up users (Singh *et al.*, 2023) ^[48, 50].



Source- Chergui and Kechadi, 2022 ^[13].

6.6 Examine heterogeneous and distributional effects

Average treatment effects can hide exclusion or harm. Evaluation should estimate whether outcomes differ by gender, poverty, remoteness, literacy, farm type, baseline extension access and climate exposure. Absolute benefits may favour larger farms even when percentage gains are similar, while requirements for smartphones may select better-resourced households. Equity analysis should measure both access and distribution of benefits, including who controls additional income. Intersectional qualitative work can identify mechanisms that sample-wide regressions miss. Programmes should predefine priority groups, collect adequate subgroup samples and avoid celebratory inclusion claims based only on the number of women or marginalized farmers registered (Chesi *et al.*, 2026) ^[14].

6.7 Evaluate durability, spillovers and system effects

Outcomes are often measured soon after a campaign, so persistence is unknown. Follow-up should establish if the farmers retain knowledge, maintain practices, renew subscriptions and even update recommendations once the intervention ends. Spillovers to neighbors may amplify the benefits and thus weaken treatment-control comparisons, but should be captured along social networks and geographic proximity. System effects are changes in adviser load, responsiveness of research, private competition, public capacity, and market concentration. Digital extension may replace, complement or crowd out other information sources. Thus, long-term evaluation should assess not only how the service supports platform activity, but also whether it contributes to strengthening the broader extension system and farmer agency (Lasdun *et al.*, 2025) ^[31].

7. Persistent challenges and risks

- **The Last-Mile Digital Divide:** Gaps extend beyond connectivity to devices, digital skills, meaningful use, and access to inputs. Inclusive programmes require affordable access, local facilitation, digital literacy, service integration, and offline alternatives (Coggins *et al.*, 2022) ^[15].

- **Accuracy, Misinformation and Liability:** Incorrect guidance on farming could damage food safety, health, animal welfare, and income for farmers. Content moderation, expert review, AI safeguards, correction mechanisms, complaint systems, and third party auditing are all necessary (Ragany *et al.*, 2026) ^[42].
- **Privacy, Consent and Data Power:** Farmer data could enhance personalization but also introduce the risks for surveillance, discrimination, and exploitation. Transparent consent, data minimization, secure access, encryption, oversight, and the protection of collective data interests is required (Duncan *et al.*, 2026) ^[18].
- **Fragmentation and Interoperability:** Isolated systems and incompatible databases create duplication and hinder collaboration. Open standards, secure APIs, shared data systems, portability, and vendor lock-in protections can enable integration while preserving consent-based access (Berisha *et al.*, 2025) ^[7].
- **The Pilot-to-Scale Gap:** Pilot success may depend on intensive support that is difficult to maintain at scale. Expansion should consider demand, reliability, cost, inclusiveness, content maintenance, and institutional ownership, supported by phased rollout and independent evaluation (Ofosu-Ampong *et al.*, 2025) ^[39].

8. Designing effective and inclusive digital extension

8.1 Build hybrid, farmer-centred services

The most powerful principle of design is Digital + Human. Automated channels can deliver reminders, answer routine questions and issue general alerts, while agents assist with diagnosis, experimentation and complex decisions. A co-design process with different farmers should be conducted prior to choosing a technology, and utilize field observation, interviews and prototyping to uncover actual decision bottlenecks. Farmers, for example, will be able to select text, voice, video or in-person assistance, and will be able to seamlessly move among channels without having to repeat their history. The rules of content and service must be driven by feedback. Success of the system should be about improving farmers and their decisions and livelihoods, not

about novelty, magnitude of messages, or how sophisticated the underlying technology (Muller *et al.*, 2024) ^[36].

.2 Localize content and strengthen knowledge governance

Localization is more than just translation. Advice should be consistent with agroecology principles and with relevant crop stage, regional names, available inputs, labour calendars, market needs and regulations. Content teams need agronomists, extension practitioners, communication specialists and farmer reviewers. Each recommendation should have an owner, evidence base, geographic scope, revision date and escalation rule. Weather and pest alerts need to be updated more quickly than generalized learning material. Farmer feedback and field results should expose the weakness of content. A federated model national quality standards with distributed adaptation can deliver scientific consistency with local relevance, and prevent every project becoming a knowledge library in identical form (Yang *et al.*, 2023) ^[56].

8.3 Invest in people and local institutions

The targeting of digital investments must include extension staff, farmer organizations, rural schools, cooperatives and local service providers. Agents require ongoing capacity building in digital facilitation, data ethics, remote diagnosis and reading of automated recommendations. Farmer champions are able to demonstrate the tools and support peers, but incentives and workload must be equitable. Facilitators and governance committees should include representation of women and other marginalised groups. Research organisations ought to attend systematically to unanswered questions from the field. When community-based organizations are able to handle enrollment, content feedback, grievance redressal, and shared hardware, the digital services are enmeshed in relationships that extend beyond a software contract or externally funded initiative (Steinke *et al.*, 2021) ^[51].

8.4 Establish responsible governance and public value

Governments must support the delivery of advice on farming practices, emergency alerts and basic data infrastructure as public goods, even if some of those services are provided by private companies. We need clear rules on advisory quality, advertising, algorithmic accountability, competition, accessibility, data rights and redress. Certification may aid consumers in ascertaining which services are credible but it should not bar small innovators through high compliance costs. Public dashboards should publish quality-adjusted reach, timeliness of response, and independently verified results. Contracts must ensure continuity and data portability in the event of a vendor change. Governance may need to foster innovation and compete with commercial interests to ensure that these interests do not, behind the scenes, determine what farmers are advised to buy or grow (Amar *et al.*, 2026) ^[3].

8.5 Align finance with outcomes and inclusion

Funding based only on enrolment encourages superficial reach. Contracts and grants should be designed to reward quality engagement, responsiveness, credible learning, equitable journalism and insights from the field, and the potential for agricultural outcomes, without creating perverse

incentives. Updating content, moderating, securing and providing technical assistance must be funded through recurrent budgets. Advising on social welfare is a public good, indirectly conversing are remotely located/serving remotely located populations, etc. Farmers' organizations can aggregate demand and negotiate the terms of service, while private platforms may subsidize advice through transactions, under transparent safeguards. Clear exit strategies are needed across all models so that farmers are not abandoned without records, support or critical alerts when a provider ceases to operate (Mehrabi *et al.*, 2021) ^[35].

10. Emerging frontiers

Multimodal generative AI could also enable farmers to use speech, text, images and video in a natural conversation, making advanced advisory services more easily accessible. Next-generation systems might combine farm history, short-range weather, satellite observations, market conditions, and established agronomic knowledge to produce context-sensitive options. The bigger technical requirement is trustworthiness than fluency. It is necessary that the benchmarks cover local languages, rare but critical cases, uncertainty communication and performance on low-end devices. Human review should be commensurate with risk. AI and that helps extension agents search evidence, draft localized responses and triage cases, may create earlier value than fully autonomous advice delivered directly to the farmers themselves (Singh *et al.*, 2024) ^[49].

Digital public infrastructure, along with compatible farmer registries, have the potential to reduce duplication and enable households that qualify to more easily access extension services, insurance, credit, and programmes. These systems may enable personalization at scale, but errors of exclusion and concentration of data are extreme hazards. Registration ought not to be based on formal land titles only, and farmers require easy-to-use means to correct and appeal. Privacy-preserving data exchange, auditable access, and clean separation of administrative eligibility determination from commercial profiling are required. The aim should be to provide farmers with secure control and service portability, rather than building a single mandatory platform for all agricultural engagement (Jakku *et al.*, 2019) ^[24].

11. Research gaps and priorities

The evidence is still aggregated knowledge and short-term adoption effects, mainly, with little rigorous work on profit, resilience, nutrition, environmental performance and empowerment. Comparative studies should test which platforms of voice, video, agents, and AI are effective for different decisions and user groups. Longer-term follow-up is necessary to capture dis-adoption, maintenance, subscription and institutional change. Reports of studies should include information on fidelity of implementation, costs, negative outcomes, and effects on subgroups. There is a need for more evidence from fragile, pastoral, indigenous and minority-language contexts. Common outcome definitions and open, privacy-protected evaluation resources would improve synthesis without forcing diverse farming systems into a single standardized model (Porciello *et al.*, 2022) ^[41].

Researchers should also examine how digital platforms redistribute knowledge authority and economic power.

Important questions include whether algorithmic recommendations narrow crop diversity, whether transaction platforms weaken or strengthen bargaining, and who captures value from farmer data. Evaluation must move beyond asking whether a tool “works” toward identifying for whom, under which conditions, at what cost and compared with what alternative. Participatory governance experiments, independent algorithm audits and mixed-method impact studies can reveal these system effects. Responsible research should include farmers in setting success criteria and interpreting results, particularly when interventions may reshape their autonomy, risk exposure or market relationships (Calzolari *et al.*, 2026) ^[10].

12. Conclusion

Digital agricultural extension can make advice timely, interactive, customized, and available, but technology by itself is not going to solve all the structural barriers facing smallholders. The evidence suggests modest average effects of digital information, and larger effects when tools are combined with trusted facilitation, demonstrations, and complementary services. Long-term impact depends on having appropriate local content, inclusive design, capable institutions, sustainable finance, responsible data governance, and rigorous evaluation that goes beyond tracking registrations and the number of messages. The choice is not between digital and traditional extension. It is whether to build accountable hybrid systems that enlarge farmers knowledge, options, agency and resilience while ensuring innovation reaches those most likely to be excluded.

References

1. Abate GT, Bernard T, Makhija S, Spielman DJ. Accelerating technical change through ICT: Evidence from a video-mediated extension experiment in Ethiopia. *World Development*. 2023;161:106089.
2. Abdulai AR, Kc KB, Fraser E. What factors influence the likelihood of rural farmer participation in digital agricultural services? Experience from smallholder digitalization in Northern Ghana. *Outlook on Agriculture*. 2023;52(1):57-66.
3. Amar S, Bori N, Corvers R. From collection to control: Data governance, digital technologies, and the politics of inclusion in the digitalisation of smallholder agriculture. *Outlook on Agriculture*. 2026;55(1):19-27.
4. Baffoe-Bonnie A, Martin DT, Mrema F. Agricultural extension and advisory services strategies during COVID-19 lockdown. *Agricultural & Environmental Letters*. 2021;6(4):e20056.
5. Barros MV, Ferreira MB, do Prado GF, Piekarski CM, Picinin CT. The interaction between knowledge management and technology transfer: a current literature review between 2013 and 2018: MV Barros *et al.* *The Journal of Technology Transfer*. 2020;45(5):1585-1606.
6. Beach RH, Milliken C, Franzen K, Lapidus D. Meta-analysis of the impacts of digital information interventions on agricultural development. *Global Food Security*. 2025;45:100866.
7. Berisha F, Da Silva L, Tegolo E, Mooney P, Pourzolfaghar Z, Helfert M. An AI-Driven Framework for Agricultural Data Interoperability Informed by Literature and Stakeholder Insights. In: 2025 International Conference on Cybersecurity and AI-Based Systems (Cyber-AI); 2025 Sep. p. 308-316. IEEE.
8. Bizo IM, Traore B, Sidibé A, Soulé M. Effectiveness of climate information services: an evaluation of the accuracy and socio-economic benefits for smallholder farmers in Niger and Mali. *Frontiers in Climate*. 2024;6:1345888.
9. Burlig F, Jina A, Kelley EM, Lane GV, Sahai H. The value of forecasts: Experimental evidence from India. National Bureau of Economic Research Working Paper No. w32173. 2024.
10. Calzolari S, Timpanaro G, Grasso A, Vindigni G. Digital technologies and social inequalities in agriculture and rural contexts: a gap-oriented systematic mapping review. *Journal of Rural Studies*. 2026;125:104199.
11. Cattaneo MD, Idrobo N, Titiunik R. A practical introduction to regression discontinuity designs: Extensions. Cambridge: Cambridge University Press; 2024.
12. Chandra S, Ghadei K, Chennamadhava M, Ali W. Development and validation of a farmer's focused digital literacy scale: a new measurement tool. 2024.
13. Chergui N, Kechadi MT. Data analytics for crop management: a big data view. *Journal of Big Data*. 2022;9(1):123.
14. Chesi ALC, Cho MA, Azong Cho MN, Ramoelo A. A Systematic Literature Review: The Influence of Technical, Operational and Structural Factors on the Adoption of Digital Agriculture Among Small-Scale Farmers in Sub-Saharan Africa. *Sustainability*. 2026;18(13):6734.
15. Coggins S, McCampbell M, Sharma A, Sharma R, Haefele SM, Karki E, *et al.* How have smallholder farmers used digital extension tools? Developer and user voices from Sub-Saharan Africa, South Asia and Southeast Asia. *Global Food Security*. 2022;32:100577.
16. Cole SA, Fernando AN. ‘Mobile’izing agricultural advice technology adoption diffusion and sustainability. *The Economic Journal*. 2021;131(633):192-219.
17. Delfani P, Thuraga V, Banerjee B, Chawade A. Integrative approaches in modern agriculture: IoT, ML and AI for disease forecasting amidst climate change. *Precision Agriculture*. 2024;25(5):2589-2613.
18. Duncan E, Ruder SL, KC KB, Wittman H, Fraser E. The political economy of agricultural data governance: Farmer perspectives on trust in data sharing. *Journal of Rural Studies*. 2026;123:104076.
19. Fabregas R, Kremer M, Schilbach F. Realizing the potential of digital development: The case of agricultural advice. *Science*. 2019;366(6471):eaay3038.
20. Fielke S, Taylor B, Jakku E. Digitalisation of agricultural knowledge and advice networks: A state-of-the-art review. *Agricultural Systems*. 2020;180:102763.
21. Gholami MJ, Al Abdwani T. The rise of thinking machines: A review of artificial intelligence in contemporary communication. *Journal of Business, Communication & Technology*. 2024;3(1):29-43.
22. Glewwe P, Todd P. Impact evaluation in international development: Theory, methods, and practice. Washington, DC: World Bank Publications; 2022.
23. High C, Singh N, Nemes G. Artificial intelligence for agricultural extension: Supporting transformative

- learning among smallholder farmers. *Journal of Development Policy and Practice*. 2026;11(1):61-80.
24. Jakku E, Taylor B, Fleming A, Mason C, Fielke S, Sounness C, *et al.* "If they don't tell us what they do with it, why would we trust them?" Trust, transparency and benefit-sharing in Smart Farming. *NJAS: Wageningen Journal of Life Sciences*. 2019;90(1):1-13.
 25. Jones-Garcia E, Singaraju N, Davis K, Koo J. Asking the right question: Toward a research agenda for responsible GAI in agricultural extension. *Advancements in Agricultural Development*. 2026;7(2):35-49.
 26. Kansime MK, Alawy A, Allen C, Subharwal M, Jadhav A, Parr M. Effectiveness of mobile agri-advisory service extension model: Evidence from Direct2Farm program in India. *World Development Perspectives*. 2019;13:25-33.
 27. Kansime MK, Tambo JA, Mugambi I, Bundi M, Kara A, Owuor C. COVID-19 implications on household income and food security in Kenya and Uganda: Findings from a rapid assessment. *World Development*. 2021;137:105199.
 28. Khatri A, Lallawmkimi MC, Rana P, Panigrahi CK, Minj A, Koushal S, *et al.* Integration of ICT in agricultural extension services: A review. *Journal of Experimental Agriculture International*. 2024;46(12):394-410.
 29. Klerkx L, Jakku E, Labarthe P. A review of social science on digital agriculture, smart farming and agriculture 4.0: New contributions and a future research agenda. *NJAS: Wageningen Journal of Life Sciences*. 2019;90(1):1-16.
 30. Krishnamoorthi S, Koh SS, Ang MCY, Teo MJT, Jie RA, Dinish US, *et al.* Advancements in Plant Diagnostic and Sensing Technologies. *Advanced Sensor Research*. 2025;4(8):e00045.
 31. Lasdun V, Harou AP, Magomba C, Guereña D. Peer learning and technology adoption in a digital farmer-to-farmer network. *Journal of Development Economics*. 2025;176:103496.
 32. Levi R, Rajan M, Singhvi S, Zheng Y. The impact of unifying agricultural wholesale markets on prices and farmers' profitability. *Proceedings of the National Academy of Sciences*. 2020;117(5):2366-2371.
 33. Li B, Zhuo N, Ji C, Zhu Q. Influence of smartphone-based digital extension service on farmers' sustainable agricultural technology adoption in China. *International Journal of Environmental Research and Public Health*. 2022;19(15):9639.
 34. Meena V, Meena KC, Goyal MC, Meena LK, Kumar R. Social media used by the farmers in sharing farm information. *Asian Journal of Agricultural Extension, Economics & Sociology*. 2022;40(10):954-960.
 35. Mehrabi Z, McDowell MJ, Ricciardi V, Levers C, Martinez JD, Mehrabi N, *et al.* The global divide in data-driven farming. *Nature Sustainability*. 2021;4(2):154-160.
 36. Muller A, Steinke J, Dorado H, Keller S, Jiménez D, Ortiz-Crespo B, *et al.* Challenges and opportunities for human-centered design in CGIAR. *Agricultural Systems*. 2024;219:104005.
 37. Mutuku B, Akuffobe-Essilfie M, Kansime M, Duah S, Oppong-Mensah B, Mibei H, *et al.* Understanding gender disparities in access to digital advisory services among women and men farmers in Ghana. *Frontiers in Sustainable Food Systems*. 2026;10:1614245.
 38. Nyoni RS, Bruelle G, Chikowo R, Andrieu N. Targeting smallholder farmers for climate information services adoption in Africa: A systematic literature review. *Climate Services*. 2024;34:100450.
 39. Ofosu-Ampong K, Abera W, Mesfin T, Abate T. Digital agro-advisory tools in the global south: a behavioural analysis of impacts, and future directions. *Discover Agriculture*. 2025;3(1):40.
 40. Pacal I, Kunduracioglu I, Alma MH, Deveci M, Kadry S, Nedoma J, *et al.* A systematic review of deep learning techniques for plant diseases. *Artificial Intelligence Review*. 2024;57(11):304.
 41. Porciello J, Coggins S, Mabaya E, Otunba-Payne G. Digital agriculture services in low- and middle-income countries: A systematic scoping review. *Global Food Security*. 2022;34:100640.
 42. Ragany M, Wolfert S, Dara R. The governance of artificial intelligence in agriculture: A review and future research directions. *Outlook on Agriculture*. 2026;00307270261450225.
 43. Rajkhowa P, Qaim M. Personalized digital extension services and agricultural performance: Evidence from smallholder farmers in India. *PLoS One*. 2021;16(10):e0259319.
 44. Rohit J, Bal SK, Anshida Beevi CN, Nagasree K, Ravi Shankar K, Nirmala G, *et al.* Exploring farmers' communication pattern and satisfaction regarding the adoption of Agromet advisory services in semi-arid regions of southern India. *Frontiers in Sustainable Food Systems*. 2024;7:1284880.
 45. Scherr TF, Hardcastle A, Moore CP, Majji D, Kuhns LM, Garofalo R, *et al.* Exploring digital health user engagement: General app usage patterns from a clinical trial with the mLab app. *PLOS Digital Health*. 2026;5(6):e0001452.
 46. Sen LTH, Phuong LTH, Chou P, Dacuyan FB, Nyberg Y, Wetterlind J. The opportunities and barriers in developing interactive digital extension services for smallholder farmers as a pathway to sustainable agriculture: A systematic review. *Sustainability*. 2025;17(7):3007.
 47. Shams MY, Gamel SA, Talaat FM. Enhancing crop recommendation systems with explainable artificial intelligence: A study on agricultural decision-making. *Neural Computing and Applications*. 2024;36(11):5695-5714.
 48. Singh NK, Sunitha NH, Tripathi G, Saikanth DRK, Sharma A, Jose AE, *et al.* Impact of digital technologies in agricultural extension. *Asian Journal of Agricultural Extension, Economics & Sociology*. 2023;41(9):963-970.
 49. Singh N, Wang'ombe J, Okanga N, Zelenska T, Repishti J, Mishra S, *et al.* Farmer.Chat: Scaling AI-powered agricultural services for smallholder farmers. *arXiv preprint arXiv:2409.08916*. 2024.
 50. Singh R, Slotznick W, Stein D. Digital tools for rural agriculture extension: Impacts of mobile-based advisories on agricultural practices in Southern India. *Journal of the Agricultural and Applied Economics Association*. 2023;2(1):4-19.

51. Steinke J, Van Etten J, Muller A, Ortiz-Crespo B, van de Gevel J, Silvestri S, *et al.* Tapping the full potential of the digital revolution for agricultural extension: An emerging innovation agenda. *International Journal of Agricultural Sustainability*. 2021;19(5-6):549-565.
52. Tambo JA, Chaudhary M, Mugambi I, Manjari M, Munireddappa MH, Khanna K, *et al.* Promoting sustainable pest management through digital decision support tools: Insights from India. *Agricultural Systems*. 2026;237:104823.
53. Urdu D, Berre AJ, Sundmaeker H, Rilling S, Roussaki I, Marguglio A, *et al.* Aligning interoperability architectures for digital agri-food platforms. *Computers and Electronics in Agriculture*. 2024;224:109194.
54. Vaidya B, Rana H, Sharma SR. Adoption of Digital Agro-Advisory Services Among Smallholder Farmers: Patterns of the Innovation-Decision Process. *Bodhi: An Interdisciplinary Journal*. 2023:313-345.
55. Yadav B, Maurya AS, Patel S, Kumar R, Kumar A. Assessing the Role of Digital Platforms in Strengthening Agricultural Extension Services: Advisory to Empowerment. *Indian Journal of Extension Education*. 2026;62(2):47-53.
56. Yang P, Wang X, Ou Y, Kim J, Lee S. Handbook on establishing and operating multi-actors agricultural innovation platforms. Food & Agriculture Organization. 2023.
57. Yuan Y, Sun Y. Practices, challenges, and future of digital transformation in smallholder agriculture: Insights from a literature review. *Agriculture*. 2024;14(12):2193.