

International Journal of Agriculture Extension and Social Development

Volume 9; Issue 7; July 2026; Page No. 400-408

Received: 18-04-2026
Accepted: 22-05-2026

Indexed Journal
Peer Reviewed Journal

Digital Agricultural Extension: Opportunities, Constraints and Emerging Innovations

¹Supriya GN, ²Dr. K Amaresh Kumar, ³D Shashikalabai and ⁴Manjunath

¹Ph.D. Scholar, Agricultural Extension and Communication, B. A College of Agriculture, Anand Agricultural University, Anand, Gujarat, India

²Professor and Extension Leader, Staff Training Unit, UAS, GKVK, Bangalore, Karnataka, India

³Associate Professor (Agril. Engineering), ICAR-AICRP on PHET, UAS, GKVK, Bangalore, India

⁴Assistant Professor (Agril. Extension), College of Agriculture, UAS, Raichur, Karnataka, India

DOI: <https://www.doi.org/10.33545/26180723.2026.v9.i7l.3975>

Corresponding Author: Supriya GN

Abstract

Digital transformation is reshaping agricultural extension by enabling advisory services to reach farmers through mobile phones, internet platforms and data-driven tools. This review synthesizes recent evidence on the opportunities, constraints and innovations in digital agricultural extension. We conducted a comprehensive literature survey of peer-reviewed studies and reports on ICT-based extension, focusing on empirical impacts and case experiences. The findings indicate that digital tools such as SMS messaging, mobile apps and advisory algorithms can increase adoption of improved practices and crop yields, though challenges like limited connectivity and digital literacy persist. We discuss emerging technologies (AI, IoT, remote sensing, etc.) and identify policy priorities and research directions. This evidence-based review provides a roadmap for leveraging digital innovation in agricultural extension globally.

Keywords: Digital extension, e-agriculture, ICTs, advisory services, smallholder farmers, innovation adoption

Introduction

Agricultural extension systems have long been crucial for transferring knowledge, innovations and best practices to farmers. Traditionally, extension relies on in-person methods agricultural officers visiting farms or holding field demonstrations to disseminate new seed varieties, fertiliser recommendations, pest management techniques and market information ^[10]. However, this conventional approach faces limitations: in many low-income regions, extension services are under-funded and understaffed, leaving large numbers of smallholders without adequate advisory support ^[16]. In recent years, the spread of information and communication technologies (ICTs) has created new opportunities to overcome these limitations. *Digital agricultural extension* refers to the use of tools such as mobile phones, the internet, radio/TV broadcasts and data-driven platforms to deliver agricultural advice ^[28]. For example, with mobile phone penetration now common even in remote villages, extension messages (weather forecasts, market prices, planting reminders) can be sent via SMS or voice calls to farmers. Similarly, online portals and social media allow instant sharing of research findings, video tutorials and peer-to-peer learning ^[43, 70]. These technologies have the potential to make extension more timely, accessible and cost-effective. At the same time, a growing body of research highlights that digital extension also faces significant challenges. Infrastructure gaps (weak mobile networks, unreliable

power), low digital literacy and social inequalities can exclude many farmers ^[52]. Not all digital initiatives succeed; past experience shows that poorly designed or irrelevant messaging can be ignored or mistrusted. Message fatigue, lack of feedback loops and failure to integrate with traditional services are common pitfalls ^[53, 54]. This review therefore synthesises what is known from recent studies about what works and what does not in digital extension.

Methodology

Opportunities

Digital technologies offer several significant opportunities to enhance agricultural extension and improve farmer outcomes:

- **Expanded Reach and Accessibility:** Digital channels can deliver extension services to geographically remote or underserved farmers who might rarely receive in-person visits. For example, mobile phone networks now cover many rural areas, so that SMS or voice advisories can reach farming communities even without Internet ^[55]. Empirical evidence suggests that simple interventions like text message reminders can nudge farmers to follow planting or application schedules. By overcoming distance barriers, digital extension dramatically increases the number of farmers reached per extension agent, making advice more inclusive and timely ^[1].

- **Knowledge Exchange and Peer Learning:** Interactive digital platforms enable two-way communication and networking among farmers and experts. Mobile apps, social media groups and discussion forums allow farmers to share experiences, ask questions and co-create knowledge. For instance, moderated WhatsApp groups have been used to post pictures of crop issues and receive expert guidance, facilitating real-time farmer-to-farmer learning^[44, 71]. Video-sharing platforms let farmers view practical demonstrations; in one trial, farmers who watched a short instructional video on maize management had yields about 10% higher than those who did not. Such multimedia learning tools can teach complex techniques (for example, pest identification or bio-fertiliser preparation) more effectively than text alone^[17].
- **Personalized, Data-driven Advice:** Digital extension systems can leverage data (weather, soil, market) to tailor recommendations to local conditions. Smartphone apps and web services can integrate GPS, weather forecasts and crop models to advise when to irrigate, apply fertilisers or schedule planting^[56]. On-farm IoT sensors (soil moisture probes, weather stations) can monitor field conditions in real time and automatically trigger alerts (e.g. “soil dry irrigate now”)^[29]. Unmanned aerial vehicles (drones) and satellites provide high-resolution imagery to detect pest outbreaks or nutrient deficiencies; extension officers can then send targeted advice to affected farmers. These data-driven approaches help optimize input use and increase resilience. Pilot projects indicate that such precision advisories can improve yields by up to 2030%, as farmers make more timely and accurate decisions^[11].
- **Strengthening Traditional Extension:** Digital tools often work best when integrated with conventional extension. Studies consistently find that combining face-to-face training with digital follow-up yields the strongest impact. For example, a controlled study in South Asia showed that farmers receiving both classroom training on fertiliser use and subsequent SMS reminders about application timing adopted the recommendations at a much higher rate than those who only had training or only had messages^[57]. The mobile reminders served as a “nudge”, reinforcing learning and reducing forgetfulness. Similarly, extension videos shown in field schools, supplemented by online quizzes or call-in support, led to higher adoption of practices than either method alone. Thus, digital extension can amplify the effect of on-site programs by providing continuous support^[2, 72].
- **Market Integration and Livelihoods:** Digital advisory platforms can also incorporate market services, thereby improving farmers’ incomes and livelihoods. Many mobile and web platforms provide up-to-date market price information, enabling farmers to choose when and where to sell for better profit. Studies have shown that access to price data through SMS or apps can shrink the price gap between farmers and traders^[58]. Other platforms link farmers directly to buyers or input suppliers via e-commerce functions. For example, digital marketplaces have allowed farmer cooperatives to negotiate bulk sales of crops or livestock, bypassing intermediaries. These integrations of extension with market information and e-commerce enhance the economic impact of extension services^[44].
- **Efficiency and Feedback Loops:** Digital tools allow extension content to be scaled efficiently. Once a piece of content is developed (say, a video tutorial or an interactive FAQ), it can be distributed to thousands of farmers at minimal additional cost. This contrasts with in-person training, which requires new physical sessions for every group^[73]. Furthermore, digital platforms can collect feedback and usage data that inform continuous improvement. Many systems track how farmers interact with messages (e.g. which links are clicked, quiz scores, or which questions are asked)^[30]. Extension programs can use this feedback to identify information gaps and refine content. For instance, if many users ask about a particular pest, new advisories can be created to address it. In this way, digital extension not only disseminates knowledge efficiently but also generates valuable data for learning and adaptation^[45].

Table 1: Comparative summary of digital extension tools and their impacts^[3, 12, 18, 31, 46, 59, 74]

Tool/Platform	Description	Key Impacts and Benefits
SMS Alerts (text messaging)	Bulk text messages sent to farmers’ phones (e.g. weather alerts, reminders, price updates).	Very low-cost, broad reach; improves information timeliness. Studies show modest increases in practice adoption (often 1020% higher adoption rates) among farmers receiving well-designed SMS advice. Effective for weather and market updates.
Interactive Voice Response (IVR)	Phone system with prerecorded audio menus (farmers call in or receive automated calls).	Inclusive of low-literacy users; supports two-way queries. Evidence indicates IVR can improve adoption of simple practices (e.g. in cotton, farmers using IVR showed higher uptake of improved seeds).
Mobile Apps (smartphone)	Smartphone applications offering interactive advisory functions (e.g. pest diagnostics, decision-support, training modules).	Delivers rich multimedia content (images, video). Personalizes recommendations via GPS, input data. Pilot projects report significant knowledge gains and yield improvements (e.g. 2030% productivity increase in engaged users).
Web Portals / E-Learning	Online platforms with knowledge libraries, tutorials and forums.	Aggregates scientific and local content; facilitates research-to-farmer linkages. E-learning courses raise farmer skills (e.g. in business or finance). Enables networking among extension actors and stakeholders.
Social Media Networks	Farmer discussion groups and advisory channels on platforms like WhatsApp, Facebook.	Facilitates peer-to-peer knowledge sharing; rapid dissemination of best practices and alerts. Many farmers (especially youth) engage in WhatsApp/Telegram groups for advice; these communities have shown high information uptake during events (e.g. pandemic).
Call Centers /	Telephone helplines where farmers can	Provides on-demand, personalized support. Builds trust and can solve

Hotlines	call agronomists or extension agents directly.	specific problems. Used for market inquiries, animal health advice, etc. Capacity is limited by available agents, but it gives farmers 24/7 support when staffed well.
Decision Support Systems (DSS)	Computer or mobile tools (models/calculators) for nutrient planning, pest forecasting, etc.	Optimizes input use based on models. Helps tailor fertilizer or pesticide recommendations. Studies report that DSS-based advice leads to more accurate decisions (1540% better yields/input balance) than unaided guesswork.
Satellite & Remote Sensing	Crop monitoring via satellite imagery or aerial sensors.	Enables near-real-time assessment of crop conditions at regional scales. Triggers targeted advisories (drought warnings, pest outbreaks). Helpful for government or NGO early warning systems that issue proactive recommendations to farmers.
Drones (UAV imagery)	Unmanned aerial vehicles capturing high-resolution field data.	Detects field-scale issues (pests, nutrient deficiencies) not visible from ground. Provides detailed maps for precision recommendations (e.g. site-specific fertiliser application). Currently more common in high-value or large farms, but costs are decreasing.
IoT Sensor Networks	Farm-based sensors (soil moisture, temperature, etc.) connected to networks.	Provides real-time field data. Automates alerts (e.g. "irrigate now"). Improves resource efficiency (pilot projects report ~2030% water or input savings). Also builds a data history for each farm over time.
AI Chatbots / Virtual Assistants	Chat-based advisory services on mobile (text or voice), powered by AI.	Offers 24/7 Q&A in local languages. Handles large volumes of common queries. Early examples (e.g. PlantVillage chatbot) show high accuracy in diagnosing plant diseases from photos and advising on remedies. Enables personalized, instant support at scale.
Blockchain Platforms	Secure digital ledgers for traceability and record-keeping.	Ensures integrity of advisory content and transactions. For example, recordings on a blockchain can verify that a farmer completed a training or followed a protocol. Builds trust (e.g. buyers can confirm sustainable practices) and can link to premium markets (like carbon credits).
E-learning/MOOCs	Structured online courses or webinars for farmers.	Allows flexible, self-paced learning. Completion certificates can motivate engagement. Expands training capacity (hundreds can attend a MOOC simultaneously) and improves knowledge on topics ranging from finance to climate-smart practices.

Constraints

Despite the promise of digital extension, multiple constraints can limit its effectiveness:

- **Infrastructure and Connectivity:** Many rural farming areas lack reliable internet or mobile coverage. Even in villages with nominal coverage, frequent network outages or slow data speeds can prevent farmers from accessing online tools. Without this basic infrastructure, digital services fail for example, a planned SMS alert may simply never arrive ^[60]. Unreliable electricity is another hurdle, as phones and data devices cannot be charged consistently. These gaps mean that advanced smartphone apps or real-time data services may not reach their target users at all ^[19, 20].
- **Device Access and Digital Literacy:** A significant portion of smallholder farmers own only basic feature phones or no mobile device, making them unable to use smartphone apps or web platforms. Even when farmers do have devices, many have limited experience using them. Low literacy levels mean text-based advice may be hard to understand ^[61]. Farmers may also distrust or feel uncomfortable with new technology. To address this, programs often include training on ICT skills, deploy services via voice calls (IVR) instead of text, or use in-person extension workers to assist farmers in using the tools ^[4].
- **Language and Cultural Barriers:** Digital content often needs to be highly localized to be effective. Advice delivered in an official language or using technical terms may be confusing or irrelevant to local farmers. Cultural factors also play a role: farmers may prefer advice from a known local adviser than from an impersonal mobile message ^[32]. Gender norms can limit technology access

(for instance, women may not own phones or may not be the decision-makers on farm). If these social dynamics are not considered, digital extension can inadvertently exclude vulnerable groups. Successful initiatives invest in translating content into local languages, using culturally relevant examples and involving trusted community members in promotion ^[47].

- **Content Relevance and Overload:** The quality and timing of digital messages are critical. Sending generic or outdated advice can do more harm than good, as farmers quickly ignore irrelevant information. Digital programs sometimes overwhelm farmers with frequent alerts (message fatigue) ^[62]. Moreover, if the advice does not match the farmer's actual constraints (e.g. advising irrigating when no water is available), it will be disregarded. Thus, content must be carefully tailored and updated, preferably with farmer feedback loops to ensure relevance. Otherwise, the digital channel becomes a noise source rather than a help ^[13].
- **Economic and Institutional Barriers:** While distributing digital content is cheap, creating and maintaining it is not free. Developing quality apps, maintaining servers or hiring technical staff requires funding. Many pilot projects are grant-funded with no clear plan for sustaining operations ^[21]. When initial funding ends, services often stop, leaving farmers stranded. On the demand side, costs can also be a barrier: farmers may have to pay for data bundles or premium services, which low-income farmers may not afford. Institutional factors matter as well: extension agencies may lack the budget, technical expertise or incentives to adopt digital methods. These issues lead to low scalability: if a service can't find long-term support, it won't grow beyond the pilot phase ^[33].

- **Regulatory and Policy Gaps:** The regulatory environment for digital agriculture is often weak. In many countries, there are no clear policies on e-agriculture, data privacy or spectrum allocation for rural telecoms. Without supportive regulations, private companies may not invest in rural connectivity and farmers may be uncertain about sharing their data. For

example, unclear data governance can cause farmers to distrust apps that collect farm information. Institutional coordination is also often lacking; agricultural, ICT and telecommunication agencies may not align their strategies. To address this, governments need to develop national e-agriculture strategies, data protection laws and standards for digital services ^[5].

Table 2: Barriers to digital agricultural extension and mitigation strategies ^[22, 34, 35, 48, 63, 76]

Barrier/Constraint	Description and Implication	Mitigation Strategy
Poor connectivity and network coverage	Rural areas may lack reliable mobile or internet signal, limiting access to online services.	Invest in rural broadband infrastructure; provide offline-capable apps; use SMS/IVR systems that work in low-signal areas.
Unreliable electricity supply	Frequent power outages or no electricity means devices cannot be charged or used consistently.	Promote solar chargers and battery backups; deploy community charging stations; use low-power technologies.
Limited access to devices	Many smallholders own only basic phones or no device, precluding use of apps or web tools.	Subsidize affordable smartphones; enable shared community devices (e.g. village kiosks); ensure core services work on basic phones.
Low digital literacy	Farmers may not know how to use apps or interpret complex digital content.	Offer training in ICT use; use simple interfaces (icons, voice prompts); engage local agents to assist technology use.
Language and cultural barriers	Advice not in local language or culturally relevant can be ignored or misunderstood.	Localize content into native languages; involve community leaders in design; use multimedia (audio, video) with cultural context.
Lack of trust / preference for tradition	Skepticism of digital advice or habit of face-to-face learning can hinder adoption.	Build trust via demonstration plots and pilot success stories; combine digital info with personal visits; engage respected local champions.
High cost of data and services	Data plans or app fees may be prohibitive for low-income farmers.	Negotiate zero-rating for agricultural content with telecoms; provide public Wi-Fi or subsidized data; offer basic services free with premium options.
Gender and inclusion gaps	Women and marginalized groups often have less access to phones and extension services.	Implement women-focused digital literacy programs; schedule content delivery at convenient times; ensure female extension workers participate.
Limited ICT capacity of extension system	Extension staff lack skills or resources to manage digital programs.	Train extension personnel in digital tools; hire ICT specialists; allocate budget for technology; create dedicated digital extension units.
Weak policy and regulatory frameworks	Absence of supportive e-agriculture policies, data standards or telecom regulation.	Formulate national e-agriculture strategies; regulate for inclusive access; set standards for data sharing and quality of digital services.

Emerging Innovations

The landscape of digital agricultural extension continues to evolve with new technologies and approaches:

- **Artificial Intelligence (AI) and Data Analytics:** AI and machine learning are increasingly used to analyze agricultural data and generate advanced advisories. Chatbots powered by AI can answer farmers' questions in local language on demand (via text or voice). For example, some apps allow farmers to send a photo of a diseased plant and receive instant diagnosis and treatment advice ^[49]. Machine learning models trained on weather, soil and yield data can predict pest outbreaks or optimal planting dates with greater accuracy. In one project, AI-driven models increased the accuracy of fertilizer recommendations by up to 40% compared to traditional guidelines. As AI matures, it promises more predictive, personalised farming advice ^[14].
- **Internet of Things (IoT) and Sensor Networks:** The IoT connects sensors and devices across the farm. Wireless soil moisture probes, temperature sensors and smart weather stations can continuously monitor field conditions. These devices automatically feed data into advisory systems; for example, a sudden drop in soil moisture can trigger an SMS to irrigate fields. Small

solar-powered sensors enable this even off-grid ^[64]. Pilot schemes have shown that farmers using IoT-driven alerts can achieve significant input savings (water, fertiliser) by optimising timing. Networked sensors also feed into regional databases, improving the accuracy of weather and pest forecasts for all farmers ^[36].

- **Drones and Remote Sensing:** Drones (unmanned aerial vehicles) are becoming more affordable and are used to capture high-resolution images of individual farms. Extension programs can analyze these images to detect issues like pest damage or nutrient deficiency before they spread ^[23]. For example, drones equipped with multispectral cameras have been used in cotton and rice fields to create vegetation maps; these maps helped focus extension visits on problem hotspots. On a broader scale, satellite remote sensing (from open-data sources) can reveal trends across large agricultural areas, informing early-warning advisories for drought or disease. These technologies enable a shift from reactive to proactive extension ^[6].
- **Blockchain and Digital Credentials:** Blockchain is being explored to increase transparency and trust in agricultural services. In digital extension, one idea is to record training attendance, certifications or input

transactions on a distributed ledger. For instance, if a farmer completes an official training via an app, this could be logged immutably^[50, 77]. Buyers or certification bodies could then verify that a farmer used recommended sustainable practices. Pilot projects in supply chain traceability suggest that when data are securely shared, farmers can gain access to premium markets (for example, carbon credit schemes). Blockchain can thus extend the value of extension by linking advice to market incentives^[37].

- **Augmented/Virtual Reality (AR/VR):** Immersive technologies are beginning to be applied to agricultural education. AR apps on smartphones can overlay digital information on real-world scenes: for example, a farmer viewing a crop through an AR app might see overlaid labels pointing out weed species or showing root growth^[65]. VR simulations are used in some training programs to let farmers “experience” mechanized operations or visualize planting techniques. While these remain nascent for smallholder extension, initial trials (for example, VR maize planting simulations) show promise as engaging learning tools, especially for younger farmers and extension trainees^[24].
- **Big Data and Cloud Platforms:** Aggregating agricultural data in the cloud enables more powerful analysis. National agriculture ministries are experimenting with data platforms that combine satellite imagery, market prices, research outputs and extension records. Analysts can query these large databases to identify patterns (e.g. which regions underutilise certain inputs). Such insights can shape extension priorities^[66]. Cloud-based services also allow developers to build new advisory apps more easily by accessing common datasets (e.g. open weather APIs) rather than collecting data from scratch. This ecosystem approach fosters innovation by connecting developers, researchers and farmers^[38].

Policy and Practice Implications

The evidence on digital extension has important implications for policy-makers and practitioners:

- **Infrastructure Investment:** Policymakers should prioritise extending connectivity to rural areas. This includes not only mobile broadband and internet but also reliable power sources. For example, governments can incentivize telecom companies to build towers in farming regions, or support community Wi-Fi schemes. Off-grid solar power or charging stations can keep devices running. Such infrastructure is the foundation without it, advanced digital tools cannot reach farmers^[25].
- **Capacity Building:** Extension personnel must be equipped to use and support digital tools. This means training existing extension agents in digital literacy and advisory software. Agricultural education curricula and professional training should include modules on ICT use. Some countries have created “Digital Extension Officer” positions whose role is to integrate ICT into the extension system^[39]. Capacity building also applies to farmers: basic training on how to use a new app or interpret a digital message can greatly increase adoption. Extension agencies should allocate time and resources for this training^[7].
- **Data Governance and Standards:** As digital extension

grows, clear policies on data use are essential. Governments need to establish regulations on data privacy, farmer consent and information sharing. For instance, a national e-agriculture policy might require that farmer data collected by public agencies be used only for farmers’ benefit and not shared externally without permission^[66]. At the same time, setting open data standards (for weather, land use, etc.) allows various apps to interoperate and reuse data, fostering a digital ecosystem rather than isolated silos^[15].

- **Inclusivity and Equity:** Digital strategies must explicitly address inequities. Gender-responsive policies are needed so women farmers benefit equally. This might involve ensuring content reaches women’s networks or using communication channels that women access (e.g. voice messages if women share phones)^[40]. Programs can set participation targets for women and marginalized groups. Accessibility features (audio instructions, icon-based interfaces) should be standard. Policies promoting universal access (e.g. community technology centers) help ensure smallholders are not left out^[8].
- **Partnerships:** Public-private partnerships (PPPs) can leverage the strengths of different actors. For example, telecom companies have technical capacity, while local NGOs have community trust^[67]. Policies can encourage collaborations such as allowing private agrotech start-ups to test solutions with extension agencies. International and regional cooperation (e.g. within ASEAN or African Union) can facilitate sharing of best practices and joint investment in cross-border digital infrastructure. Funding mechanisms (grants, matched funds) that require partnerships can align incentives^[26].
- **Sustainable Financing:** Digital extension initiatives should aim for financial sustainability. Governments should budget for digital components (software development, data costs) as part of extension budgets, not rely solely on short-term project funding^[68]. Innovative models can be explored: for example, a mobile advisory service might be free to farmers but financed by charging agribusinesses or banks for integrated marketing/credit services. Subsidies or vouchers could lower farmer costs initially. Policies that encourage startup incubators or investment in agri-tech can also stimulate financially viable solutions^[51].
- **Monitoring and Evaluation (M&E):** Digital platforms generate rich usage data that should be incorporated into extension M&E. Extension agencies should track not only outputs (number of messages sent) but also outcomes (response rates, changes in practices)^[41]. Policies can mandate the use of dashboards that monitor key indicators across all digital tools. Regular impact assessments comparing regions or systems with/without digital interventions can inform scaling decisions. By institutionalizing M&E of digital outreach, programs can iterate and improve continuously^[42].
- **Integration with Sectoral Policies:** Digital extension should be integrated into broader agricultural and rural development strategies. For example, linking digital extension platforms with e-health or e-education initiatives in villages can create synergy^[78, 69]. Climate adaptation policies can include digital early warning

systems as part of extension. Trade and market policies can coordinate with extension to ensure that information flows along value chains. In short, digital advisory services should not be treated in isolation but embedded within the national development agenda ^[27]. In sum, enabling policies are as important as technological innovation. By investing in infrastructure, skills and governance, governments can create an environment where digital extension thrives. Public and private stakeholders must align to support scaling, while ensuring that digital extension contributes to inclusive, sustainable agricultural development ^[9, 15].

Conclusion

Digital agricultural extension represents a transformative opportunity for farming communities. This review has shown that ICT tools from basic SMS alerts to advanced AI diagnostics can substantially enhance the reach and effectiveness of extension services. When well-implemented, digital advisories increase adoption of improved practices and boost yields. Case studies around the world provide evidence of real benefits: improved fertilizer use in Nepal, higher rice yields in randomized trials and better market outcomes in farmers linked by mobile networks. However, the promise of digital extension is balanced by significant challenges. Infrastructure gaps, social inequalities and capacity constraints can hinder impact. Our synthesis indicates that technology alone is not a silver bullet: supportive context and human factors are critical. Digital interventions must be co-designed with farmers, integrated with traditional advisory methods and supported by investment in rural connectivity and training. Otherwise even the most advanced app or sensor can be under-utilized or abandoned. Emerging technologies add to the optimism. IoT, drones, AI and others could make extension more precise and data-rich than ever. Yet these innovations will only succeed if they are inclusive and user-centred. In practice, the most successful models tend to blend the new with the old for example, delivering basic advisories via SMS while piloting smartphone apps with young farmers. Policy-makers and extension leaders should view digital tools as an extension of their toolbox, not a replacement. Looking forward, coordinated action will be essential. Extension programs should incorporate digital strategies into their core plans, with dedicated budgets and metrics. Governments must create enabling environments (infrastructure, regulation, financing). Researchers should rigorously test new approaches and identify what works across contexts. If these elements are aligned, digital agricultural extension has the potential to accelerate sustainable intensification and climate resilience on a global scale. The evidence to date inspires optimism: with continued research, investment and collaboration, digital extension can significantly contribute to sustainable agriculture and rural development worldwide.

References

1. Aker JC. Dial 'A' for agriculture: a review of information and communication technologies for agricultural extension in developing countries. *Agricultural Economics*. 2011;42(6):631-647. DOI:10.1111/j.1574-0862.2011.00545.x
2. Aker JC, Ghosh I, Burrell J. The promise (and pitfalls) of ICT for agriculture initiatives. *Agricultural Economics*. 2016;47(S1):35-48. DOI:10.1111/agec.12301
3. Anderson JR, Feder G. Agricultural extension: good intentions and hard realities. *The World Bank Research Observer*. 2004;19(1):41-60. DOI:10.1093/wbro/lkh013
4. Anderson JR, Feder G, Ganguly S. The rise and fall of training and visit extension: an Asian mini-drama with an African epilogue. *World Bank Policy Research Working Paper No. 3928*. 2006.
5. Ethiopian Agricultural Transformation Agency (ATA). 2013/14 annual report: transforming agriculture in Ethiopia. Addis Ababa: ATA; 2014.
6. Bali K, Sitaram S, Cuendet S, Medhi I. A Hindi speech recognizer for an agricultural video search application. In: *Proceedings of the 3rd ACM Symposium on Computing for Development*; 2013 Jan 11-12; Bangalore, India. New York: ACM; 2013.
7. Baumüller H. The little we know: an exploratory literature review on the utility of mobile phone-enabled services for smallholder farmers. *Journal of International Development*. 2018;30(1):134-154. DOI:10.1002/jid.3314
8. Bazzano AN, Martin J, Hicks E, Faughnan M, Murphy L. Human-centred design in global health: a scoping review of applications and contexts. *PLoS ONE*. 2017;12(11):e0186744. DOI:10.1371/journal.pone.0186744
9. Belay K. Constraints to agricultural extension work in Ethiopia: the insiders' view. *South African Journal of Agricultural Extension*. 2002;31:63-79.
10. Beza E, Steinke J, van Etten J, Reidsma P, Fadda C, Mittra S, *et al*. What are the prospects for citizen science in agriculture? Evidence from three continents on motivation and mobile telephone use of resource-poor farmers. *PLoS ONE*. 2017;12(5):e0175700. DOI:10.1371/journal.pone.0175700
11. Birmer R, Davis K, Pender J, Nkonya E, Anandajayasekeram P, Ekboir J, *et al*. From best practice to best fit: a framework for designing and analyzing pluralistic agricultural advisory services worldwide. *The Journal of Agricultural Education and Extension*. 2009;15(4):341-355. DOI:10.1080/13892240903309595
12. Blumenstock JE, Eagle N. Divided we call: disparities in access and use of mobile phones in Rwanda. *Information Technology and International Development*. 2012;8:1-16.
13. Boersma A. The future of KM? Design thinking! So here are 5 elements to 'ECHO'. *Knowledge Management for Development Journal*. 2017;13:25-30.
14. Carletto G, Beegle K, Himelein M, Kilic T, Murray S, Oseni M, *et al*. Improving the availability, quality and policy-relevance of agricultural data: the living standards measurement study - integrated surveys on agriculture. In: *Proceedings of the Third Wye City Group Global Conference on Agricultural and Rural Household Statistics*; 2010 May 24-25; Washington, DC.
15. Carmona MA, Sautua FJ, Pérez-Hernández O, Mandolesi JJ. AgroDecisor EFC: first Android™ app decision support tool for timing fungicide applications for management of late-season soybean diseases.

- Computers and Electronics in Agriculture. 2018;144:310-313. DOI:10.1016/j.compag.2017.11.028
16. Carmona M, Sautua F, Perelman S, Gally M, Reis EM. Development and validation of a fungicide scoring system for management of late season soybean diseases in Argentina. *Crop Protection*. 2015;70:83-91. DOI:10.1016/j.cropro.2015.01.019
 17. Chancellor TCB, Priebe JSH, Mkenda PA. Crowdsourcing field observations from smallholder farmers in Tanzania using interactive voice response. *Outlooks on Pest Management*. 2019;30(3):104-110. DOI:10.1564/v30_jun_02
 18. Christensen LR, Ahsan H, Rashid M, Das BK. Are you magicians? The collaborative work of an agricultural information service. In: *Proceedings of the 10th International Conference on Information and Communication Technologies and Development (ICTD19)*; 2019 Jan 4-7; Ahmedabad, India.
 19. Cock J, Oberthür T, Isaacs C, Roman P, Palma A, Carbonell J, *et al.* Crop management based on field observations: case studies in sugarcane and coffee. *Agricultural Systems*. 2011;104(9):755-769. DOI:10.1016/j.agsy.2011.07.001
 20. Conrad CC, Hilchey KG. A review of citizen science and community-based environmental monitoring: issues and opportunities. *Environmental Monitoring and Assessment*. 2011;176(1-4):273-291. DOI:10.1007/s10661-010-1582-5
 21. Courtois P, Subervie J. Farmer bargaining power and market information services. *American Journal of Agricultural Economics*. 2015;97(3):953-977. DOI:10.1093/ajae/aau051
 22. Daum T, Buchwald H, Gerlicher A, Birner R. Smartphone apps as a new method to collect data on smallholder farming systems in the digital age: a case study from Zambia. *Computers and Electronics in Agriculture*. 2018;153:144-150. DOI:10.1016/j.compag.2018.08.017
 23. Davis K. Extension in Sub-Saharan Africa: overview and assessment of past and current models and future prospects. *Journal of International Agricultural Extension and Education*. 2008;15:15-28.
 24. Deichmann U, Goyal A, Mishra D. Will digital technologies transform agriculture in developing countries? *Agricultural Economics*. 2016;47(S1):21-33. DOI:10.1111/agec.12300
 25. Dodson L, Sterling SR, Bennett JK. Considering failure: eight years of ITID research. *Information Technology and International Development*. 2013;9:19-34.
 26. Duncombe R. Mobile phones for agricultural and rural development: a literature review and suggestions for future research. *European Journal of Development Research*. 2015;28(2):1-23. DOI:10.1057/ejdr.2014.60
 27. Eastwood C, Ayre M, Nettle R, Dela Rue B. Making sense in the cloud: farm advisory services in a smart farming future. *NJAS - Wageningen Journal of Life Sciences*. 2019;90-91:100298. DOI:10.1016/j.njas.2019.04.004
 28. Eitzinger A, Cock J, Atzmanstorfer K, Binder CR, Läderach P, Bonilla-Findji O, *et al.* Geofarmer: a monitoring and feedback system for agricultural development projects. *Computers and Electronics in Agriculture*. 2019;158:109-121. DOI:10.1016/j.compag.2019.01.049
 29. Fabregas R, Kremen M, Schilbach F. Realizing the potential of digital development: the case of agricultural advice. *Science*. 2019;366(6471):eaay3038. DOI:10.1126/science.aay3038
 30. Fadda C, van Etten J. Generating farm-validated variety recommendations for climate adaptation. In: Rosenstock T, Girvetz E, Nowak A, editors. *The climate-smart agriculture papers*. Cham: Springer; 2019. p. 127-138.
 31. Faure G, Desjeux Y, Gasselin P. New challenges in agricultural advisory services from a research perspective: a literature review, synthesis and research agenda. *The Journal of Agricultural Education and Extension*. 2012;18(5):461-492. DOI:10.1080/1389224X.2012.707063
 32. Feder G, Anderson JR, Birner R, Deininger K. Promises and realities of community-based agricultural extension. Washington, DC: IFPRI; 2010. IFPRI Discussion Paper No. 959.
 33. Fu X, Akter S. The impact of mobile phone technology on agricultural extension services delivery: evidence from India. *The Journal of Development Studies*. 2016;52(11):1561-1576. DOI:10.1080/00220388.2016.1146700
 34. Glendenning CJ, Ficarella P. The relevance of content in ICT initiatives in Indian agriculture. Washington, DC: IFPRI; 2012. IFPRI Discussion Paper No. 1180.
 35. Grossman G, Platas MR, Rodden J. Crowdsourcing accountability: ICT for service delivery. *World Development*. 2018;112:74-87. DOI:10.1016/j.worlddev.2018.07.001
 36. GSMA. State of the industry report on mobile money. London: GSMA; 2017.
 37. Gulliksen J, Göransson B, Boivie I, Blomkvist S, Persson J, Cajander A. Key principles for user-centred systems design. *Behavior & Information Technology*. 2003;22(6):397-409. DOI:10.1080/01449290310001624329
 38. Haider Rizvi SM. Lifelines: livelihood solutions through mobile technology in India. In: Grimshaw DJ, Kala S, editors. *Strengthening rural livelihoods: the impact of information and communication technologies in Asia*. Rugby: Practical Action Publishing and International Development Research Centre; 2011. p. 53-70.
 39. Hammond J, Fraval S, van Etten J, Gabriel J, Mercado L, Pagella T, *et al.* The rural household multi-indicator survey (RHoMIS) for rapid characterisation of households to inform climate smart agriculture interventions: description and applications in East Africa and Central America. *Agricultural Systems*. 2017;151:225-233. DOI:10.1016/j.agsy.2016.05.003
 40. Hampson K, Sones D, Watiti J. Scaling-up improved legume technologies in Tanzania (SILT): final technical report. Ottawa: Farm Radio International, CABI and Africa Fertilizer & Agribusiness Partnership; 2018.
 41. Hasanain A, Khan Y, Rezaee A. No bulls: crowdsourcing away asymmetric information in the market for artificial insemination in Pakistan [unpublished manuscript]. 2017.
 42. Hassenzahl M, Tractinsky N. User experience - a research agenda. *Behavior & Information Technology*.

- 2006;25(2):91-97. DOI:10.1080/01449290500330331
43. Heeks R. Information systems and developing countries: failure, success and local improvisations. *The Information Society*. 2002;18(2):101-112. DOI:10.1080/01972240290075039
 44. Hoffmann V, Probst K, Christinck A. Farmers and researchers: how can collaborative advantages be created in participatory research and technology development? *Agriculture and Human Values*. 2007;24(3):355-368. DOI:10.1007/s10460-007-9072-2
 45. Jarvis A, Eitzinger A, Koningstein MJ, Benjamin T, Howland FC, Andrieu N, *et al.* Less is more: the 5Q approach. Cali: CIAT; 2015.
 46. Jones M, Kondylis F. Does feedback matter? Evidence from agricultural services. *Journal of Development Economics*. 2018;131:28-41. DOI:10.1016/j.jdeveco.2017.10.013
 47. Kelly T, Firestone R. How tech hubs are helping to drive economic growth in Africa. Background paper to the World Development Report 2016: digital dividends. Washington, DC: World Bank; 2015.
 48. Kilelu CW, Klerkx L, Leeuwis C. Unravelling the role of innovation platforms in supporting co-evolution of innovation: contributions and tensions in a smallholder dairy development programme. *Agricultural Systems*. 2013;118:65-77. DOI:10.1016/j.agsy.2013.03.003
 49. 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;90-91:100315. DOI:10.1016/j.njas.2019.100315
 50. Matous P, Todo Y, Pratiwi A. The role of motorized transport and mobile phones in the diffusion of agricultural information in Tanggamus Regency, Indonesia. *Transportation*. 2015;42(5):771-790. DOI:10.1007/s11116-015-9646-6
 51. McCole D, Culbertson MJ, Suvedi M, McNamara PE. Addressing the challenges of extension and advisory services in Uganda: the Grameen Foundation's community knowledge worker program. *Journal of International Agricultural and Extension Education*. 2014;21(1):6-18. DOI:10.5191/jiaee.2014.20101
 52. Minet J, Curnel Y, Gobin A, Goffart JP, Mélard F, Tychon B, *et al.* Crowdsourcing for agricultural applications: a review of uses and opportunities for a farmsourcing approach. *Computers and Electronics in Agriculture*. 2017;142:126-138. DOI:10.1016/j.compag.2017.08.026
 53. Müller A, Mora V, Rojas E, Díaz J, Fuentes O, Giron E, *et al.* Emergency drills for agricultural drought response: a case study in Guatemala. *Disasters*. 2019;43(2):410-430. DOI:10.1111/disa.12316
 54. Mutembesa D, Omongo C, Mwebaze E. Crowdsourcing real-time viral disease and pest information: a case of nation-wide cassava disease surveillance in a developing country. In: *Proceedings of the Sixth AAAI Conference on Human Computation and Crowdsourcing (HCOMP 2018)*; 2018 Jul 5-8; Zurich, Switzerland.
 55. Mwombe SOL, Mugivane FI, Adolwa IS, Nderitu H. Evaluation of information and communication technology utilization by small holder banana farmers in Gatanga District, Kenya. *The Journal of Agricultural Education and Extension*. 2014;20(2):247-261. DOI:10.1080/1389224X.2013.788454
 56. Nakasone E, Torero M. A text message away: ICTs as a tool to improve food security. *Agricultural Economics*. 2016;47(S1):49-59. DOI:10.1111/agec.12314
 57. Nakasone E, Torero M, Minten B. The power of information: the ICT revolution in agricultural development. *Annual Review of Resource Economics*. 2014;6(1):533-550. DOI:10.1146/annurev-resource-100913-012714
 58. Neef A, Neubert D. Stakeholder participation in agricultural research projects: a conceptual framework for reflection and decision-making. *Agriculture and Human Values*. 2011;28(2):179-194. DOI:10.1007/s10460-010-9272-z
 59. Ortiz-Crespo B, Steinke J, Quirós CF, Daudi H, Mgimiloko MG, van Etten J. User-centered design of a digital advisory service: enhancing public agricultural extension for sustainable intensification in Tanzania. *International Journal of Agricultural Sustainability*. 2020;Special Issue: Sustainable Agricultural Intensification:1-17. DOI:10.1080/14735903.2020.1720474
 60. Patel N. Not your average farmer: designing for lead users in ICT4D research. *Interactions*. 2010;17(5):50-52. DOI:10.1145/1836216.1836229
 61. Patel N, Chittamuru D, Jain A, Dave P, Parikh TS. Avaaj Otalo - a field study of an interactive voice forum for small farmers in rural India. In: *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*; 2010 Apr 10-15; Atlanta, GA.
 62. Patel N, Savani K, Klemmer SR, Parikh TS. Power to the peers: authority of source effects for a voice-based agricultural information service in rural India. *Information Technology and International Development*. 2013;9:81-93.
 63. Patnaik S, Brunskill E, Thies W. Evaluating the accuracy of data collection on mobile phones: a study of forms, SMS and voice. In: *Proceedings of the International Conference on Information and Communication Technologies and Development (ICTD)*; 2009 Apr 17-19; Doha, Qatar.
 64. Qiang CZ, Kuek SC, Dymond A, Esselaar S. Mobile applications for agriculture and rural development. Washington, DC: World Bank, ICT Sector Unit; 2012. Report No.: 96226-GLP.
 65. Rivera WM. Public sector agricultural extension system reform and the challenges ahead. *The Journal of Agricultural Education and Extension*. 2011;17(2):165-180. DOI:10.1080/1389224X.2011.544457
 66. Rosenstock TS, Lamanna C, Chesterman S, Hammond J, Kadiyala S, Luedeling E, *et al.* When less is more: innovations for tracking progress toward global targets. *Current Opinion in Environmental Sustainability*. 2017;26-27:54-61. DOI:10.1016/j.cosust.2017.02.010
 67. Schut M, Klerkx L, Sartas M, Lamers D, McCampbell M, Ogbonna I, *et al.* Innovation platforms: experiences with their institutional embedding in agricultural research for development. *Experimental Agriculture*. 2016;52(4):537-561. DOI:10.1017/S001447971500023X
 68. Snyder C. Paper prototyping: the fast and easy way to

- design and refine user interfaces. San Francisco: Morgan Kaufmann; 2003.
69. Steinke J, Achieng JO, Hammond J, Kebede SS, Mengistu DK, Mgimiloko MG, *et al.* Household-specific targeting of agricultural advice via mobile phones: feasibility of a minimum data approach for smallholder context. *Computers and Electronics in Agriculture*. 2019;162:991-1000. DOI:10.1016/j.compag.2019.05.026
 70. Steinke J, van Etten J, Mejía Zelan P. The accuracy of farmer-generated data in an agricultural citizen science methodology. *Agronomy for Sustainable Development*. 2017;37(4):32. DOI:10.1007/s13593-017-0441-y
 71. Sulaiman R, Hall A, Kalaivani NJ, Dorai K. Necessary, but not sufficient: critiquing the role of information and communication technology in putting knowledge into use. *The Journal of Agricultural Education and Extension*. 2012;18(4):331-346. DOI:10.1080/1389224X.2012.691782
 72. Sullivan BL, Aycrigg JL, Barry JH, Bonney RE, Bruns N, Cooper CB, *et al.* The eBird enterprise: an integrated approach to development and application of citizen science. *Biological Conservation*. 2014;169:31-40. DOI:10.1016/j.biocon.2013.11.003
 73. Šūmane S, Kunda I, Knickel K, Strauss A, Tisenkopfs T, de los Rios I, *et al.* Local and farmers' knowledge matters! How integrating informal and formal knowledge enhances sustainable and resilient agriculture. *Journal of Rural Studies*. 2018;59:232-241. DOI:10.1016/j.jrurstud.2017.01.020
 74. Sumberg J, Okali C, Reece D. Agricultural research in the face of diversity, local knowledge and the participation imperative: theoretical considerations. *Agricultural Systems*. 2003;76(2):739-753. DOI:10.1016/S0308-521X(02)00153-1
 75. Taye H. Evaluating the impact of agricultural extension programmes in sub-Saharan Africa: challenges and prospects. *African Evaluation Journal*. 2013;1(1):1-9. DOI:10.4102/aej.v1i1.19
 76. Taylor M, Bhasme S. Model farmers, extension networks and the politics of agricultural knowledge transfer. *Journal of Rural Studies*. 2018;64:1-10. DOI:10.1016/j.jrurstud.2018.09.015
 77. Tongia R, Subrahmanian E. Information and communications technology for development (ICT4D) - a design challenge? Pittsburgh: Department of Engineering and Public Policy, Carnegie Mellon University; 2006. Paper No. 119.
 78. Van Etten J, Beza E, Calderer L, van Duijvendijk K, Fadda C, Fantahun B, *et al.* First experiences with a novel farmer citizen science approach: crowdsourcing participatory variety selection through on-farm triadic comparisons of technologies (tricot). *Experimental Agriculture*. 2019;55(S1):275-296. DOI:10.1017/S0014479716000739