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From field to future: The evolution of agricultural extension in the digital age for sustainable and revitalized rural economies

[1]Sanchita Roy, [2]Sambuddha Mukherjee, [3]Yogesh BM, [4]Dr. Gyanendra Singh, [5]Dr. P Kalaiselvi, [6]Ritik Raj, [7]Sumana Balo and [8]Nikita Diwakar

[1]Assistant Professor, School of Agriculture, Dev Bhoomi Uttarakhand University, Dehradun, Uttarakhand, India

[2]Research Scholar (Agricultural Economics), Department of Economics & Sociology, Punjab Agricultural University, Ludhiana, Punjab, India

[3]Research Scholar, Department of Agricultural Extension, Indian Agricultural Research Institute, New Delhi, India

[4]SRF (NICRA), ICAR-ATARI, Kanpur, Zone-III, Uttar Pradesh, India

[5]Associate Professor (ENS), ICAR- Krishi Vigyan Kendra, Tamil Nadu Agricultural University, Salem, Tamil Nadu, India

[6]Research Scholar, Department of Botany, Plant Physiology and Biochemistry (BPP&BC), College of Basic Science and Humanities, Dr. Rajendra Prasad Central Agricultural University, Pusa, Bihar, India

[7]Department of Soil Science and Agricultural Chemistry, Faculty of Agricultural Science (FAS), Siksha 'O' Anusandhan (Deemed to be University), Bhubaneswar, Odisha, India

[8]Ph.D. Research Scholar (Food and Nutrition), Punjab Agricultural University, Ludhiana, Punjab, India

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Corresponding Author: Sambuddha Mukherjee

Abstract

Agricultural extension has long been the bridge connecting scientific research with farming practice. Traditionally, extension agents traveled to villages to demonstrate new techniques and train farmers, working to increase productivity and improve livelihoods. Today, however, the field of extension is rapidly evolving. Digital technologies including mobile phones, satellites, data analytics and artificial intelligence are transforming how farmers receive advice and support. This article traces the history of agricultural extension and examines its modern transformation in the "digital age." We discuss how innovations in communication and information technology have expanded the reach and speed of extension services worldwide. The discussion highlights both global and Indian experiences, noting key milestones, pioneering figures and innovative programs. We also consider the impact of digital extension on sustainable rural economies, including increased yields, income growth and environmental benefits. Finally, we address challenges (like the digital divide and content relevance) and outline future directions to fully realize the potential of digital extension for sustainable rural development.

Keywords: Agricultural extension, digital agriculture, sustainable development, rural economy, farm advisory services, technology adoption, climate-smart farming, India

Introduction

Agricultural extension is the process of translating scientific research into practical knowledge for farmers [h]. Historically, it has involved experts and extension officers visiting rural communities to teach improved farming methods, demonstrate new crop varieties and address local agricultural challenges [37]. In an era of climate change, population growth and resource constraints, effective extension is more important than ever. At the same time, the advent of digital technology is revolutionizing farming itself [49]. Now, information can flow through mobile phones, smart phones, Internet platforms, radios and television, supplementing or even replacing some traditional face-to-face methods [69]. This article explores the journey "from field to future" in agricultural extension how knowledge sharing has evolved and how it can support sustainable and revitalized rural economies. We draw on experiences worldwide, with special focus on India, to see how innovation and policy are reshaping extension [23].

Historical Evolution of Agricultural Extension

The roots of agricultural extension extend far back in history. Ancient civilizations understood the value of sharing farming advice. For example, clay tablets from 1800 B.C. in Mesopotamia recorded instructions on irrigation and pest control [95]. In imperial China (circa 6th century B.C. onwards), state-sponsored agricultural texts were distributed among farmers to improve grain production [24]. As literacy and printing spread, early agricultural books and pamphlets helped disseminate best practices in many cultures. By the medieval and Renaissance periods, European landowners and peasants exchanged knowledge in farmers' guilds and clubs [70]. The first known organized agricultural society was formed near Milan in 1548 and throughout the 17th-18th centuries "agricultural improvist" groups met to discuss crop rotations, fertilization and new tools [11]. These were precursors to modern extension, emphasizing that farming improvements require both technical know-how and social institutions to spread it. A major milestone came in the 19th century with the establishment of formal institutions. In 1862, the United States passed the Morrill Land-Grant Act, creating agricultural colleges nationwide. Later, in 1914 the Smith-Lever Act established the Cooperative Extension Service, linking those colleges to rural communities [50]. This model of university-led extension was emulated around the globe. For instance, Horace Plunkett in Ireland (late 1800s) pioneered cooperatives and agricultural education, helping Irish farmers adopt modern methods. His 1896 committee advocated organized farmer training and credit coops, laying early foundations for what would become structured extension [71]. In colonial and post-colonial contexts (Africa, Asia, Latin America), national governments and foreign advisors likewise set up extension services in the early 20th century [38].

In India, formal extension efforts gained momentum in the mid-20th century. The Imperial Council of Agricultural Research (ICAR) was established in 1929 and after independence it expanded farm science centers. In the 1960s, the Green Revolution dramatically showcased extension's role. Pioneers like Norman Borlaug (Nobel Laureate) and M. S. Swaminathan introduced high-yield wheat and rice varieties [72, 73]. Borlaug's work in Mexico and South Asia increased global wheat output and Swaminathan championed those innovations in India [52]. Crucially, extension agents taught millions of smallholder farmers the new planting and irrigation techniques [25]. As a result, rice and wheat production in India soared, averting famine. Later, in 1975 India launched the Krishi Vigyan Kendra (Farm Science Centre) program. These KVKs acted as local hubs where scientists and local educators trained farmers in better seeds, pest control and management practices. Other innovators also shaped extension thinking. Sociologist Everett Rogers developed the "Diffusion of Innovations" theory in the 1960s, explaining how new ideas spread among people [74]. His model identifying innovators, early adopters and so on became a conceptual backbone of extension planning. Agricultural economists and educators similarly contributed by evaluating which extension methods were most effective [39]. Over decades, extension models diversified: *top-down* programs by government coexisted with more *participatory* approaches. In the late 1980s and 1990s, the introduction of Farmer Field Schools in Asia allowed groups of farmers to learn through hands-on experimentation, especially in integrated pest management. These schools emphasized that farmers learn best from each other under expert facilitation [12].

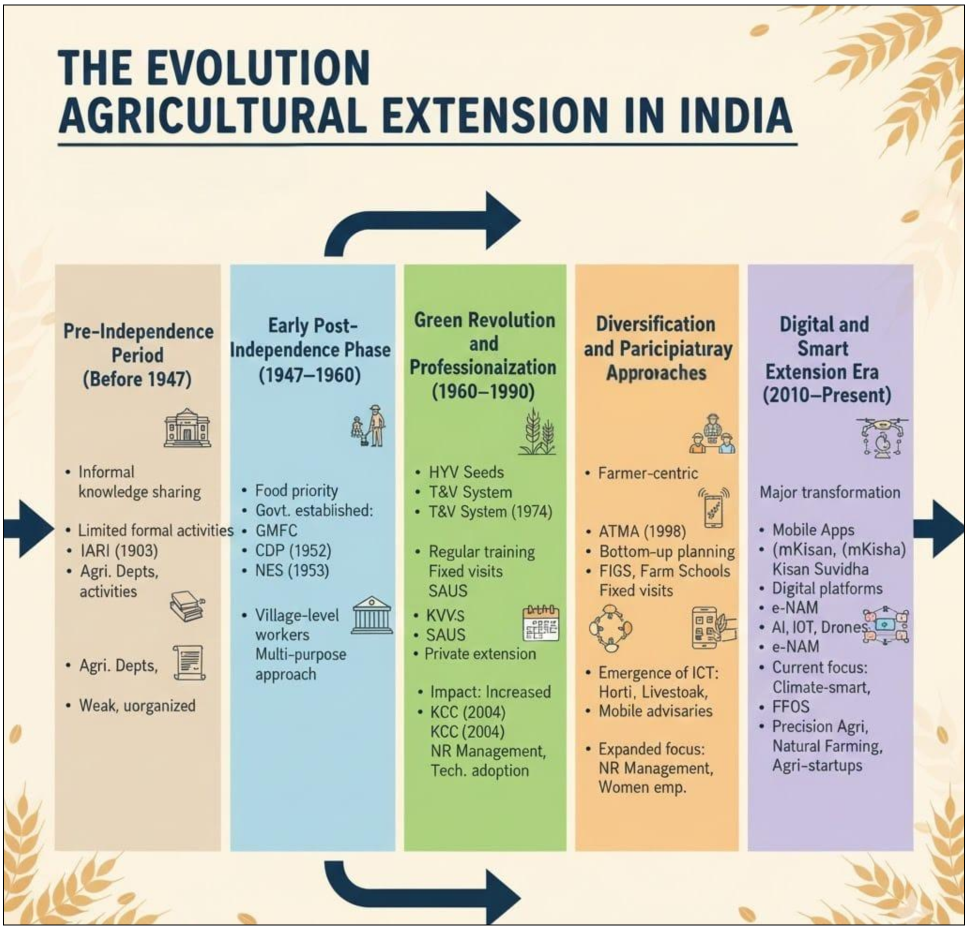

Table 1 below highlights key milestones in the history of agricultural extension, combining global events with developments specific to India. It illustrates how the field evolved from ancient advice dissemination to modern digital programs [75, 91].

Year/Period	Event/Initiative	Description/Impact
1800 BCE	Mesopotamian clay tablets	Earliest written farm advice on irrigation and pest control.
535 AD	Chinese treatise *Essential Techniques…*	Widely printed agriculture manual for landowners and peasants.
1548	Rezzato Agricultural Society (Italy)	First known agri-society promoting farmer knowledge exchange.
1862	Morrill Land-Grant Act (USA)	Established agricultural colleges; served as extension base.
1896	Horace Plunkett's Committee (Ireland)	Advocated organized co-ops and farmer training in Ireland.
1914	Smith-Lever Act (USA)	Created U.S. Cooperative Extension Service linking universities.
1929	Establishment of ICAR (India)	Central research body; later guided extension and education.
1960s	Global/Indian Green Revolution	Introduction of high-yield varieties; led by Borlaug & Swaminathan.
1975	Launch of Krishi Vigyan Kendras (India)	Farm Science Centres for local farmer training were instituted.
1980s-1990s	Farmer Field Schools (Asia, Africa)	Participatory training approach taught pest management in fields.
1990s	Rise of mobile phones and internet	Digital communication begins to expand extension reach.
2000	e-Choupal initiative (ITC, India)	Internet kiosks linked farmers to markets, weather and advice.
2004	Kisan Call Centres (India)	Toll-free helplines launched for real-time farmer queries.
2013	mKisan SMS portal (India)	Government SMS/IVR service for weather, price info and alerts.
2020-2024	AI4AI and Digital Agri Mission (India)	AI advisory (Saagu Baagu) piloted; national digital agri-infra.

Traditional vs. Digital Extension Approaches

For much of the 20th century, agricultural extension was based on in-person communication. Extension officers (often scientists or trained agronomists) physically traveled to villages organized group meetings under banyan trees or demonstrated techniques on farmer's fields [26]. They distributed pamphlets, explained seed spacing, fertilizer doses and showed new implements [53]. This traditional model built strong personal relationships: farmers could ask questions directly and receive context-specific answers [76]. Training was typically periodic (aligned with cropping seasons) and followed established curricula. The strength of this approach was its personal touch and deep tailoring to local conditions [13].

However, there were also clear limitations. Each agent could reach only a limited number of farmers, constrained by travel time and budget [77]. In many countries the ratio of farmers to extension agents was high often hundreds or thousands of farmers per agent. This meant large gaps, especially in remote or marginalized areas [54]. As a result, many smallholders remained unaware of the latest improvements. Traditional extension also tended to deliver information slowly: if a disease outbreak occurred, it could be days or weeks before any advice reached all affected farmers. Moreover, collecting feedback and monitoring adoption was labor-intensive, relying on paper surveys and agent reports [40].

In contrast, the digital era has added new dimensions to extension. Information and communication technologies (ICT) now supplement or even replace some face-to-face methods. Mobile phones allow voice calls or SMS alerts to be sent quickly. The Internet and apps enable videos, interactive voice response and social media interactions [27]. These tools vastly increase scale: a single broadcast message or social media post can reach thousands of farmers at once. They also improve timeliness: weather warnings, market prices or pest alerts can be pushed out immediately. Digital systems can record usage data and feedback automatically, enabling two-way communication at scale [14].

Table 2 summarizes key differences between traditional and digital extension approaches. It highlights how aspects like communication mode, reach, cost and interactivity contrast under the two models [55, 78].

Aspect	Traditional Extension	Digital Extension
Communication mode	In-person visits, group meetings, printed bulletins	Mobile calls/SMS, smartphone apps, web platforms, social media
Scale of reach	Limited by number of agents and travel (hundreds of farmers)	Very large; potentially nationwide or global reach via networks
Timeliness of information	Periodic (e.g. monthly bulletins or seasonal visits)	Real-time or instant updates (weather alerts, market prices)
Cost per farmer	High (agent travel and salary per farm served)	Low (digital messaging costs shared among many users)
Personalization	Moderately high (agent knows local conditions)	High (data-driven targeting by location, crop type, season)
Content format	Verbal/print (demonstrations, charts, pamphlets)	Multimedia (videos, audio clips, images, interactive modules)
Interactivity	Two-way (farmer questions answered in person or meetings)	Variable (chatbots, call-back services, online forums, live chat)
Feedback & data collection	Manual (reports by agents, printed surveys)	Automated (digital forms, app analytics, recorded calls)
Technology requirement	Low (pen, paper, simple tools)	High (requires phones, internet connectivity, power)
Accessibility (timing)	Fixed schedule (training days, field visits)	Anytime access (24/7 mobile service, on-demand information)
Record-keeping	Limited, mostly manual	Extensive (digital logs of queries, farm profiles, chat history)
Market connectivity	Indirect (post-harvest visits, limited market info)	Direct (online marketplaces, real-time price platforms)
Scalability	Slow (each new region needs personnel)	Rapid (a single platform can scale nationwide)
Environmental footprint	Moderate (agent travel, paper use)	Lower per user (digital content replaces printing)
Innovation uptake speed	Slow (information moves farm-to-farm gradually)	Fast (news can go viral via networks and media)

This comparison shows that digital extension dramatically changes the game. For example, a smartphone app can deliver location-specific weather forecasts and planting advice instantaneously, whereas a traditional program might rely on a printed pamphlet or a lecture weeks earlier [56]. However, it is important to note that digital tools are most effective when combined with personal support. Farmers often still trust and rely on local extension workers to interpret information [79]. Modern extension models tend to blend both approaches: training community members to use digital tools or having agents facilitate video sessions in villages. This hybrid approach seeks to leverage the strengths of each method [41].

Global Digital Innovations and Case Studies

- Across the world, digital innovations are reshaping agricultural extension. The spread of mobile phones has had a particularly profound impact. Today there are over 7 billion mobile phone subscriptions globally, many in rural areas. Even basic phones can receive SMS or voice messages, making extension advice ubiquitous [1]. For instance, in sub-Saharan Africa the mobile platform *iCow* (Kenya) sends dairy farmers voice and text messages on animal husbandry, improving milk yields. *Esoko* (Ghana) provides smallholders with daily commodity prices and weather updates via SMS and web [57]. In Asia, Bangladesh's *Krishi Call Centre 16123* reaches farmers by mobile voice calls and *SMSGobeshona* in Bangladesh offers crop tips by text [28]. These services overcome literacy barriers by using voice menus and local languages, bringing science-based advice to remote regions [15].
- Beyond phones, many countries use video and social networking. Digital Green (started in India, now global) has community video "screenings" where farmers watch short clips of peers demonstrating techniques for example, using biopesticides or improved irrigation methods [58]. These videos are produced by farmers themselves under expert guidance, ensuring the content is relevant and culturally appropriate. Meanwhile, projects like OneRice in the Philippines and RiceAdvice by international research centers use mobile apps to recommend rice fertilizer application rates based on weather and soil data [80]. In Africa, the *PlantVillage Nuru* smartphone app (developed by Penn State University and partners) allows a farmer to take a photo of a crop leaf and instantly receive an AI diagnosis of pests or disease [29].
- Farm machinery and precision tools are also integrated into extension services. Platforms like HelloTractor (Nigeria) act as "Uber for tractors, " using mobile apps to match farmers with equipment owners, solving labor bottlenecks [81]. Drones are being used in countries like the U.S., Australia and China to map fields from above; combined with online analysis tools, this data is turned into actionable advice on spraying or planting density. In Europe, smartphone apps advise fruit growers on harvest timing and blockchain trials are linking farm product traceability to extension networks to promote transparency [42].
- International organizations have recognized digital extension as a key development strategy. The United Nations' Food and Agriculture Organization (FAO) runs an *e-Agriculture* initiative, hosting conferences and a knowledge exchange platform for ICT in agriculture [16]. The World Bank and CGIAR research centers support digital extension projects in Africa and Asia. For example, a CGIAR-led *Technologies for African Agricultural Transformation (TAAT)* program delivered climate-resilient seeds to 12 million farmers via a digital e-catalog and extension SMS system. In summary, the global picture is one of innovation: AI, IoT sensors, big data and mobile services are being applied to help smallholder farmers increase yields and incomes while using natural resources more sustainably [2].

Table 3 below lists notable digital tools and platforms used in agricultural extension around the world. These examples illustrate the variety of approaches from smartphone apps to helplines and show how they combine information delivery with user interaction [82, 92].

Platform/Tool/Program	Region/Country	Medium/Technology	Key Features/Benefits
e-Choupal	India	Internet kiosks/ICT	Village internet kiosks offer market prices, weather forecasts and expert advice.
mKisan	India	SMS, IVR, Web portal	Government portal sends weather alerts, agri tips; farmers send questions via SMS.
Kisan Call Centre (KCC)	India	Telephone helpline	Free multi-language voice hotline for farmer queries; responds with expert help.
Digital Green	India/Africa	Video & field agents	Locally-produced training videos (in native language) demonstrating best practices.
AgriStack (Digital Mission)	India	Data infrastructure	Digital public infrastructure (farmer IDs, land records) enabling unified services.
PlantVillage Nuru	Global (e.g. Africa, Asia)	Smartphone app (AI)	AI-based app diagnoses crop pests/diseases from leaf photos; advises control steps.
HelloTractor	Africa	Mobile app, USSD	"Uber for tractors" farmers book tractor services; increases mechanization.
WeFarm	Latin America/Africa	SMS/Chat platform	Peer-to-peer Q&A network; farmers ask questions and crowdsource answers via text.
iCow	Kenya, Africa	SMS and voice	Delivers livestock rearing tips (e.g. feeding, breeding) to dairy farmers via SMS.
Esoko	West Africa	SMS/Web	Provides market prices, weather forecasts and advisory bulletins via text and web.
Farmonaut	India/Global	Satellite data/Apps	Satellite imagery and analysis platform for crop health, soil

			moisture monitoring.
Drones and Crop Apps	Global	Drones, Mobile apps	UAVs for field mapping; connected apps for farm analytics and spray recommendations.
Pusa Krishi App	India	Smartphone app	Indian Govt app offers localized crop advisory for sowing, inputs and disease.
AGMARKNET	India	Website/SMS	Market Intelligence network; provides daily market prices and arrival data.
Kisan Suvidha App	India	Mobile app	Aggregates weather, market and pest information; has live chat with experts.
Satellite Soil Maps	India	Remote sensing	High-resolution digital maps guiding fertilizer and crop choices (1:10, 000 scale).

Digital Agriculture in India: Policies and Practices

- India presents a compelling case study of the digital extension revolution. With over 60% of its population in rural areas, India has made improving farmer livelihoods a top priority. In recent years, the government and private sector have launched numerous initiatives [17]. The National e-Governance Plan in Agriculture (NeGP-A), started in 2007, laid groundwork by creating online portals for farm data and advisories [30]. More recently, the Digital Agriculture Mission (approved 2024) has become a central focus. This mission (backed by a multi-thousand-crore investment) builds a robust digital backbone for Indian farming. Its two key pillars are *AgriStack* and the *Krishi Decision Support System (DSS)* [3].
- AgriStack is envisioned as a comprehensive digital public infrastructure: every farmer will receive a unique digital ID (like an Aadhaar for agriculture) linked to his land records, crop history and scheme benefits [83]. Geo tagged farm boundaries and a digital crop register will cover all farming households. By 2025, pilot surveys aim to map millions of farms across hundreds of districts. The Krishi DSS pillar will integrate real-time data on weather, soil moisture, water resources and crop growth to provide tailored recommendations [59]. For example, a farmer could use the DSS to decide optimal sowing dates or irrigation schedules for his precise location [84]. A related initiative is Soil Profile Mapping, in which over 1:10, 000 scale maps are being drawn for tens of millions of hectares of farmland; these detailed maps will guide nutrient management on a block-by-block basis. Collectively, these components promise to make extension advice data-driven and instantly accessible [43].
- In parallel with these national efforts, many on-the-ground services flourish. ITC's *e-Choupal* network now includes over 6, 000 kiosks serving more than 4 million farmers. The government's *mKisan* program (launched 2013) sends SMS/IVR advisories in 22 languages; over 7 million farmers are registered to receive regular weather and market updates [85]. Farmer producer organizations use private apps to manage inventories and arrange sales [60]. Startups have also entered the fray: for example, *AgroStar* and *Ninjacart* provide quality-certified inputs and demand forecasting apps, indirectly advising farmers on what and when to plant. A notable recent pilot is the AI-driven *Saagu Baagu* (Telangana state), where thousands of chili farmers received real-time AI-based pest management and quality-testing advice; this reportedly led to double the incomes for many participants in just one season [31].
- Moreover, traditional extension institutions are adopting digital tools. Krishi Vigyan Kendras (farm science centers) conduct webinars and host WhatsApp groups for farmer queries [4]. Agricultural universities live stream experimental farm tours online. The public weather service has partnered with telecom companies to send early flood and drought warnings by SMS [44]. Collectively, these examples show that India is leveraging mobile broadband, satellite connections and even social media (YouTube channels, Facebook groups) to deliver extension content [61]. The result is a fast-growing "e-extension" ecosystem. However, this innovation coexists with challenges: uneven Internet access, language diversity and the sheer scale of Indian agriculture mean that constant adaptation is required. Still, India's strategy exemplifies how a large country can use a mix of policy and technology to bring extension into the digital era [18].

Impact on Sustainable Rural Economies

Modernized extension particularly digital extension has a powerful impact on rural livelihoods and sustainability. By empowering farmers with knowledge, it directly drives several beneficial outcomes:

- **Improved Crop Productivity:** Farmers with access to timely advice achieve higher yields. For example, trials in India and Africa have shown 10-25% yield increases when smallholders follow best-practice recommendations via SMS or apps. In one long-term study in Odisha, India, rice farmers receiving weekly mobile advisories achieved about 1.7% higher yields and 4.1% more harvested output compared to controls. This kind of productivity gain helps ensure food security for communities and reduces hunger [62].
- **Increased Farm Incomes:** Better yields and quality translate into higher incomes. Digital markets and price alerts ensure farmers sell at fair rates. In the Telangana chili program (mentioned above), farmers effectively doubled their per-acre income thanks to improved quality testing and market linkages. More income lets farming households invest in education, health and diversification, boosting rural economies overall [45].
- **Resource Efficiency & Sustainability:** Digital extension frequently promotes climate-smart practices. Mobile advisories instruct farmers on optimized water use, integrated pest management (reducing chemical use) and organic soil amendments [86]. For example, satellite-based soil moisture data can trigger irrigation only when needed, saving water. By reducing waste and pollution, these practices safeguard the environment. Thus, extension contributes to more sustainable land

use and resilient food systems, aligning with global sustainability goals [32].

- **Disaster Resilience:** Early warning alerts are now a key extension service. Meteorological data can be sent instantly to farmers before extreme events (droughts, floods) [87]. Pest and disease outbreaks are flagged through digital networks, enabling rapid response. Such real-time guidance markedly reduces crop losses; some extension programs report over 20% reduction in losses during unusual weather when farmers receive SMS or app alerts. This stability protects rural incomes and livelihoods [5].
- **Market Access and Value Addition:** Digital platforms link farmers to wider markets. Farmer Producer Organizations (FPOs) use online marketplaces to sell collectively. Extension no longer ends at the farm gate: it now includes advice on post-harvest processing, packaging and even compliance with export standards (through online training modules). This integration increases value capture in the rural economy, creating jobs in storage, transport and processing [64].
- **Empowerment and Social Benefits:** Knowledge is empowering. When extension content is delivered through mobile phones or community videos, even marginalized farmers including many women can learn in private or peer groups [88]. Digital content can be provided in local dialects and via voice (overcoming literacy barriers). As a result, more farmers adopt innovations and participate in income-generating activities. Rural youths, growing up with smart phones, find agriculture more attractive when it involves data-driven decision-making, potentially reversing youth migration to cities [19].

Table 4 below contrasts key outcomes under conventional and digital extension models. It illustrates how digital methods can amplify benefits for rural economies [65, 94]:

Outcome/Indicator	Conventional Extension	Digital Extension
Farmer Reach	Narrow; one agent per few hundred farms	Massive; digital broadcasts or apps can reach thousands at once
Yield Improvement	Gradual; incremental gains per season	Faster; real-time advice and precise recommendations boost yields
Income Growth	Moderate; limited by local market access	Higher; better practices and direct market links can significantly increase earnings
Market Access	Indirect; relies on local middlemen	Direct; online markets and price info connect farmers to buyers
Input Use Efficiency	Variable; depends on farmer's discretion	Optimized; sensor data and apps guide exact fertilizer and water use
Crop Loss Reduction	Limited; knowledge of threats may lag	Significant; instant pest/weather alerts help avoid losses
Disaster Resilience	Reactive; relies on post-event support	Proactive; early warnings allow preparations for floods/droughts
Knowledge Adoption Rate	Slow; often one practice at a time	Rapid; updates and peer sharing accelerate uptake of innovations
Extension Cost per Farmer	High (travel and staffing costs)	Lower (fixed platform cost spread over many users)
Quality of Advisory	High contextual tailoring by agents	High potential tailoring through analytics, but reliant on data quality
Speed of Updates	Slow (periodic newsletters or visits)	Instant (news can be updated continuously via apps/SMS)
Youth Participation	Limited; farming seen as manual and outdated	Increasing; tech adoption makes farming attractive to youth
Gender Inclusion	Low; women often miss formal sessions	Higher potential; e.g. women can call hotlines or use voice apps
Environmental Impact	Often high inputs and waste due to limited info	Reduced; precision agriculture cuts waste and promotes eco-friendly practices
Rural Livelihoods	Farming-centered, limited diversification	Diversified; tech spurs new agri-businesses (processing, tech services)

Challenges and Barriers

Despite its promise, digital extension faces real-world obstacles. Key challenges include:

- **Digital Divide:** In many rural regions, network coverage is spotty or absent. Even where mobile networks exist, electricity outages and lack of smart phones can block access. For example, in some remote districts only 50% of villages have reliable broadband [89]. Without addressing these gaps (through infrastructure investments like rural broadband projects and solar power), digital solutions cannot reach all farmers [20].
- **Digital Literacy:** Owning a phone does not guarantee skill in using it. Older farmers and those with limited schooling may find apps and websites confusing. Voice-based systems and extensive training programs are needed so that users can navigate digital platforms and trust the information they receive [33].
- **Content Relevance and Localization:** Farmers speak many languages and grow diverse crops in varying climates. Generic advice (often in national languages or English) may not make sense locally. Extension content must be tailored: translated into local dialects and customized for specific crops and regions. Creating and maintaining this localized content is resource-intensive [6].
- **Trust and Personal Connection:** Extension work builds on trust. Some farmers may distrust computer-generated advice or chat bots, feeling that personal contact is irreplaceable. If digital services seem impersonal or fail to address specific concerns, adoption will lag. Blending digital tips with on-ground support (for example, farm visits by extension agents who explain the digital advice) can mitigate this [46].
- **Data Privacy and Ownership:** Large digital systems collect sensitive information land records, cropping data, financial transactions. Ensuring that this data is secure and used ethically is a concern. Farmers must be assured that their data will not be misused or sold without consent. Robust data governance, encryption and clear usage policies are essential [66].
- **Institutional Capacity:** Many public agricultural departments lack the technical expertise or funds to develop and maintain digital tools. Training extension staff to use technology and hiring IT professionals within these departments, is a significant organizational

change. Without this capacity building, digital projects may falter after initial pilots [34].

- **Equity and Inclusion:** There is a risk that digital extension services primarily benefit those who are already better off. Wealthier, tech-savvy farmers may reap most gains, while marginalized groups (landless, lower castes, women) may still be left out. Special programs (e.g. women-only training camps, subsidized devices) are needed to ensure equitable access [7]. Addressing these challenges requires concerted efforts. Expanding rural connectivity (for example, through projects like India's BharatNet and plans to use 5G for agriculture) lays the foundation. Simultaneously, extension agencies must partner with NGOs and tech companies to develop user-friendly services (using voice and video as much as text) [90]. In some Indian states, extension agents are being trained to conduct live digital demos via smartphones, bridging old and new. By recognizing and actively solving these barriers, stakeholders can ensure that digital extension truly reaches and benefits every farmer [21].

Future Directions and Recommendations

The future of agricultural extension will be shaped by ongoing innovation and collaboration. Key recommendations include:

- **Invest in Rural Connectivity:** Governments should accelerate electrification and build high-speed Internet infrastructure in villages. Public-private partnerships (for example, telecom providers subsidizing rural coverage) can expand access rapidly. Affordable devices (low-cost smartphones, community tablets, etc.) should be made available to farmers [47].
- **Train Extension Workers and Farmers:** Human capacity is crucial. Extension agents must be trained in ICT tools and data analysis, becoming digital coaches themselves. At the same time, farmers need basic digital literacy training (often through community programs or local cooperatives) so they can use advisory apps, SMS services and databases effectively [67].
- **Develop Localized Content:** Advisory content should be co-created with farmers, researchers and local educators. Using regional languages, local crop examples and multimedia (videos, voice messages) will make digital extension more accessible. Ensuring content reflects traditional knowledge and local conditions will boost trust and adoption [35].
- **Integrate Data Systems:** Digital platforms (like India's AgriStack) should ensure interoperability. Weather data, market info, government subsidy schemes and land records must be linked so that extension advice is holistic. This "digital public infrastructure" approach allows one app to serve multiple needs (for example, a single farmer dashboard showing soil health, weather forecast and credit options) [68].
- **Leverage Emerging Technologies:** Artificial Intelligence (AI) and machine learning can personalize advice based on big data. For instance, AI chatbots could answer farmer questions in local languages. Drone and satellite data can feed predictive models for pests or yield. Blockchain could secure farmer identities and financial transactions. These technologies should be piloted carefully in partnership with researchers and scaled if successful [8].
- **Promote Public-Private Collaboration:** Government, academia, NGOs and agribusinesses all have roles to play. For example, a state government might fund the development of a mobile advisory app, researchers contribute localized agronomy content and private companies help with distribution and user experience design. Incentives and grants can encourage startups to target smallholder farmers [36].
- **Ensure Inclusive Access:** Policies must prioritize women, the landless and marginalized communities. This might mean supporting rural women's groups with community phones or ensuring female extension agents lead programs for women farmers. Gender-sensitive design (like voice interfaces for those who cannot read) will make services more inclusive [22].
- **Continuously Monitor Impact:** Digital extension programs should include built-in monitoring and feedback loops. Data analytics can show which messages are most effective or which regions are under-served. Regular field surveys and user feedback will help refine tools. This iterative approach ensures resources are going to what works [9, 48].

Conclusion

From its origins in ancient clay tablets and farmers' gatherings, agricultural extension has transformed into a high-tech network connecting scientists and smallholders. This evolution from "field to future" is not just about technology; it is about empowering rural communities. When farmers have access to the right information at the right time whether through a village workshop or a mobile alert they make better decisions that increase yields, incomes and environmental stewardship. Digital agriculture does not replace the human touch of extension; rather, it multiplies it. A village elder using a smart phone app or a youth entrepreneur running a drone service are modern faces of the same extension mission. In the global context, digital extension services are already revitalizing rural economies. For example, precision agronomy tools have delivered up to 25% yield increases in pilot projects across Africa and smart phone-based advice in India has demonstrably reduced crop losses. In India specifically, the recent wave of e-governance (Digital India, eNAM, digital farmer IDs) is bringing previously isolated farmers into a shared market and information network. These efforts are aligned with broader goals: achieving food security (by raising production sustainably), reducing poverty (by increasing farm incomes) and meeting climate goals (by promoting efficient, low-emission farming methods). Nevertheless, challenges remain. Ensuring that digital advances serve all farmers including the poorest and least literate requires continued commitment. Extension agencies must evolve, funds must flow and partnerships must flourish. But the direction is clear: knowledge is the most powerful crop of all. By blending time-tested extension methods with cutting-edge digital tools, societies can cultivate not only better crops, but also stronger, more resilient rural communities. In conclusion, as agriculture moves steadily into the future, an inclusive and innovative extension service will be essential for sustainable and revitalized rural economies everywhere.

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