

DIGITAL AND ICT-BASED AGRICULTURAL EXTENSION SERVICES FOR ACCELERATING TECHNOLOGY ADOPTION AND SUSTAINABLE HORTICULTURAL DEVELOPMENT: A REVIEW

K.P. Vanetha¹, D. Jayaraj^{2*}, R. Naveen Kumar³, P. Sujanthiya⁴, J. Marimuthu⁵, M. Vijayapriya⁶ & M. Mathivanan⁷

¹Department of Social Science, Horticultural College and Research Institute, TNAU, Periyakulam, Theni-625604, Tamil Nadu, India

^{2&3}Department of Plantation, Spices, Medicinal and Aromatic crops, Horticultural College and Research Institute, TNAU, Coimbatore-641003, Tamil Nadu, India

⁴Department of Horticulture, Krishna College of Agriculture and Technology, Srirangapuram, Usilampatti, Madurai-625532, Tamil Nadu, India

⁵Department of Vegetable Sciences, Horticultural College and Research Institute, TNAU, Coimbatore, Tamil Nadu

⁶Department of Agricultural Microbiology, Horticultural College and Research Institute for Women, TNAU, Tiruchirappalli -620027, Tamil Nadu, India

⁷Department of Forestry, School of Agricultural Sciences, Dhanalakshmi Srinivasan University, Samayapuram, Tiruchirappalli, Tamil Nadu

*Corresponding Author: D.Jayaraj, jaysdbagrii@gmail.com

ABSTRACT

Horticulture is a crucial part of global agriculture, yet it is increasingly challenged by climate change, limited resources, and fluctuating markets. To tackle these issues, digital and ICT-based extension services have emerged as powerful solutions, enhancing access to information, improving management precision, and fostering communication between farmers. The adoption of technologies such as mobile phones, internet platforms, IoT sensors, artificial intelligence (AI), remote sensing, and big-data analytics has transformed horticultural advisory systems. These advancements facilitate real-time and location-specific interactions between farmers and experts. As a result, they aid in informed decision-making across various aspects of farming, including crop production, pest and disease management, irrigation, nutrient application, and marketing strategies. Evidence suggests that digital extension services can boost technology adoption, productivity, and resilience among farmers; however, the success of these initiatives relies on factors like infrastructure, digital literacy, affordability, and institutional backing. This review outlines the development of digital horticultural extension, underscores its significance for climate-smart and sustainable practices, and emphasizes the need for inclusive, farmer-centric, and hybrid models that blend human and digital approaches. Future research should concentrate on understanding the long-term effects, context-specific factors influencing adoption, and the creation of integrated policy frameworks that promote equitable and sustainable digital advancements in horticulture.

KEYWORDS: Digital horticulture, ICT-based extension, Climate-smart agriculture, Technology adoption, Precision farming, Sustainable development

INTRODUCTION

Horticulture is one of the most dynamic and economically vital sectors of agriculture, encompassing fruits, vegetables, plantation crops, spices, ornamentals, medicinal, and aromatic plants. These crops contribute significantly to food and nutritional security, employment generation, farm income, and export earnings. However, horticultural production is increasingly challenged by climate variability, water scarcity, soil degradation, emerging pests and diseases, labor shortages, rising input costs, and fluctuating market demand. To address these complexities, farmers must adopt improved technologies and make timely, knowledge-based decisions across the production and post-harvest chain. In this context, agricultural extension and advisory services are indispensable for disseminating scientific knowledge and facilitating the adoption of improved horticultural practices.

Agricultural extension has traditionally served as a bridge between research institutions, extension agencies, and farming communities, enabling the transfer of technologies and innovations from scientists to farmers. Conventional approaches—such as personal visits, demonstrations, training programs, farmer meetings, printed materials, and mass media—remain important but are often constrained by limited personnel, geographical barriers, high operational costs, and the sheer scale of farming populations. As Aker (2011) observed, inadequate and asymmetric access to agricultural information can hinder farmers' decision-making and adoption of technologies, while information and communication technologies (ICTs) provide opportunities to overcome these barriers.

The rapid development of ICTs has transformed conventional extension into more flexible and accessible digital systems. Mobile phones, SMS, interactive voice response (IVR), internet services, websites, mobile applications, social media, and online video platforms are increasingly used to disseminate agricultural

information. These tools allow farmers to access knowledge more rapidly and often at lower cost than traditional methods. Nakasone et al. (2014) emphasized that ICTs reduce information asymmetries and improve production and marketing decisions, while Baumüller (2018) highlighted the role of mobile-enabled services in supporting smallholder farmers' decision-making. Importantly, digital extension is not limited to one-way dissemination of information; it increasingly supports two-way communication, farmer participation, and personalized advisory services. Farmers can interact directly with extension personnel and experts through mobile applications, messaging platforms, and social media, sharing field experiences, photographs, and problems for diagnosis. Fabregas et al. (2022) demonstrated that farmers actively use digital tools to access and exchange agricultural knowledge, underscoring the importance of interactive systems that strengthen farmer–extension relationships and improve the relevance of recommendations.

The emergence of Agriculture 4.0 has further expanded the scope of ICT-based extension services. Advanced technologies such as artificial intelligence (AI), Internet of Things (IoT), remote sensing, Geographic Information Systems (GIS), drones, big-data analytics, cloud computing, and machine learning are increasingly integrated into decision-support systems. These tools generate real-time, location-specific information on crop growth, soil moisture, weather conditions, nutrient requirements, pest and disease incidence, and yield forecasts. Wolfert et al. (2017) highlighted the role of big-data technologies in supporting data-driven decision-making, while Klerkx et al. (2019) emphasized that digitalization is reshaping agricultural innovation and extension by fostering new forms of interaction among farmers, researchers, and technology providers.

Digital technologies are particularly relevant to horticulture, where crop performance is highly sensitive to weather, irrigation, nutrient availability, pest and disease pressure, and harvest timing. Advisory systems can provide timely recommendations on crop establishment, irrigation scheduling, nutrient management, integrated pest and disease management, protected cultivation, harvesting, and post-harvest handling. For instance, weather-based mobile advisories help farmers respond to rainfall variability, while AI-powered image recognition assists in pest and disease identification. Remote sensing and GIS support crop monitoring and resource management, while IoT sensors provide real-time data on soil moisture and microclimatic conditions. Adoption of these technologies is influenced by farmers' awareness, knowledge, perceived usefulness, economic benefits, and access to technical support. Digital platforms improve awareness and knowledge by offering continuous access to expert recommendations, complementing rather than replacing face-to-face extension. (Klerkx et al., 2019; Sen et al., 2025)

Beyond productivity, digital extension holds promise for sustainable horticultural development. Precision agriculture technologies enable site-specific input application, reducing unnecessary use of fertilizers, pesticides, and irrigation water. Digital weather information and early-warning systems help farmers manage climate risks, while remote sensing and sensor technologies improve resource monitoring. Trendov et al. (2019) emphasized that digital technologies can enhance productivity, efficiency, and resilience when appropriately integrated, while Lioutas et al. (2021) cautioned that their contribution to sustainability depends on thoughtful design and implementation.

In summary, digital extension represents a transformative approach to horticultural development. By integrating ICTs and advanced technologies, it enhances information access, fosters participatory learning, strengthens farmer–extension linkages, and supports sustainable resource management. While challenges such as cost, connectivity, and digital literacy remain, digital extension offers immense potential to improve efficiency, resilience, and sustainability in horticultural production, making it a cornerstone of future agricultural innovation.

2. Evolution and Concept of Digital and ICT-Based Agricultural Extension

Agricultural extension has undergone a major transformation with the advancement of information and communication technologies (ICTs). Conventional methods—such as farm visits, demonstrations, training programs, farmer meetings, and printed materials—continue to play a role but are often limited by manpower shortages, geographical barriers, high costs, and difficulties in delivering timely information to diverse farming populations. ICTs have therefore emerged as powerful tools to enhance the accessibility, speed, and efficiency of agricultural knowledge dissemination (Lio & Liu, 2006; Saravanan, 2010).

Empirical evidence highlights the strong link between ICT infrastructure and agricultural development. Lio and Liu (2006) demonstrated a positive relationship between ICT growth and agricultural productivity across countries, suggesting that ICTs function not only as communication tools but also as enablers of technology adoption and productivity gains. The widespread adoption of mobile phones marked a turning point in extension services, allowing farmers to access information on crop production, markets, weather, and inputs without direct contact with extension personnel. Fafchamps and Minten (2012) showed that SMS-based services in India improved farmers' access to information and supported better decision-making.

Mobile-enabled services have since evolved from basic information delivery to specialized advisory systems. Baumüller (2018) noted their potential to improve farm management and reduce information gaps, while also cautioning that effectiveness depends on farmers' actual usage and context. Internet-based systems and digital market platforms further expanded extension by providing timely market information. Goyal (2010) demonstrated that internet kiosks offering price data in Central India improved farmers' bargaining power and marketing decisions, underscoring the economic impact of digital information.

A key shift in digital extension has been the move from one-way communication to interactive, participatory systems. Farmers now engage directly with extension agents, researchers, and peers through mobile apps, messaging services, and online communities, sharing experiences and crop-related problems. Richardson (2006)

emphasized that such participatory communication strengthens knowledge exchange and enhances the relevance of advisory services. Mobile technologies have also enabled personalized advisory systems, tailoring recommendations to crop type, location, weather, and farmer-specific needs. Fu and Akter (2016) highlighted their role in strengthening farmer–extension communication, particularly valuable in horticulture where management practices vary widely.

The latest stage in extension evolution integrates advanced technologies such as artificial intelligence (AI), Internet of Things (IoT), remote sensing, geographic information systems (GIS), big-data analytics, cloud computing, and machine learning. These tools generate real-time, location-specific data to support predictive and precision-based recommendations on crop management, irrigation, nutrient application, pest and disease control, and yield forecasting. For horticultural crops, which are highly sensitive to environmental conditions, such digital tools provide timely, crop-specific guidance on nursery management, irrigation, fertigation, pest control, pruning, harvesting, and post-harvest handling. (Sen et al., 2025; Manzoor et al., 2025)

Despite these advances, challenges remain. Digital literacy gaps, poor connectivity, affordability issues, language barriers, and limited localized content can restrict the effectiveness of ICT-based services. Baumüller (2018) stressed that benefits depend on actual adoption and contextual suitability. Thus, successful digital extension requires careful consideration of farmers' socioeconomic conditions, technological capacity, and information needs.

Overall, the evolution of extension can be traced as a progression from face-to-face methods → mass media → mobile-based services → internet platforms → interactive digital systems → AI- and data-driven smart extension. This trajectory highlights the growing potential of ICTs to make extension more accessible, timely, participatory, and farmer-centered. For horticulture, integrating digital tools with conventional extension can enhance technology adoption, resource efficiency, climate resilience, and informed decision-making, thereby supporting sustainable agricultural development (Spielman et al., 2021; Xu et al., 2023)

3. Digital Tools and Technology Platforms for Strengthening Horticultural Extension

The rapid advancement of information and communication technologies (ICTs) has transformed agricultural extension and advisory services, offering diverse tools to enhance knowledge dissemination, farmer–expert communication, and decision-making. ICT-based extension now encompasses mobile phones, SMS, smartphone applications, websites, social media, digital videos, interactive voice response (IVR), geographic information systems (GIS), remote sensing, Internet of Things (IoT), artificial intelligence (AI), and integrated digital platforms. These innovations provide timely, location-specific information and support more efficient farm management, though their effectiveness depends on accessibility, digital literacy, and contextual relevance (Fabregas et al., 2022).

Mobile phones and SMS services remain the most accessible ICT tools, particularly in developing countries. They deliver information on crop management, weather, markets, inputs, and government programs directly to farmers. Studies in India demonstrated that SMS-based services improved access to agricultural information and strengthened farmer–extension communication (Fafchamps & Minten, 2012; Fu & Akter, 2016). For horticulture, mobile alerts on rainfall, irrigation, and pest outbreaks are especially valuable, though their impact depends on usage and socioeconomic conditions (Baumüller, 2018).

Smartphone applications and digital advisory platforms have expanded extension beyond basic SMS, integrating services such as weather forecasts, crop calendars, pest diagnosis, nutrient recommendations, irrigation scheduling, and market information. Multimedia features like photos, videos, and GPS enhance interactivity and personalization. In India, mobile-based ICT innovations are increasingly recognized for their potential to deliver farmer-oriented information (Paliwal & Kumari, 2023).

Internet-based services provide farmers with access to digital libraries, online portals, and knowledge repositories, offering updated information on crop technologies, pest management, and markets. Internet kiosks in Central India improved farmers' marketing decisions and performance, highlighting the economic benefits of digital information (Goyal, 2010).

Social media platforms such as WhatsApp, YouTube, and Facebook facilitate peer-to-peer learning and rapid dissemination of advisories, pest alerts, and market information. They enable farmers to share experiences and locally adapted solutions, strengthening participatory extension (Suchiradipta & Saravanan, 2016). For horticulture, social media is particularly useful for demonstrating grafting, pruning, and nursery practices.

Video-based extension provides visual demonstrations of complex horticultural practices such as grafting, pruning, fertigation, and post-harvest handling. Farmer-to-farmer video approaches have proven effective in participatory learning, offering flexible and repeatable access to knowledge (Zossou et al., 2009).

IVR systems deliver voice-based agricultural information, making extension more inclusive for farmers with limited literacy. These services provide crop, weather, and market information in local languages, reducing barriers to digital adoption (Harris et al., 2024).

GIS and remote sensing strengthen spatial analysis in extension, offering insights into crop health, acreage, drought, and resource availability. For horticulture, these tools support monitoring, stress detection, and yield estimation, enabling targeted interventions. (Klerkx et al., 2019; Xu et al., 2023).

IoT technologies use sensors to collect real-time data on soil moisture, temperature, humidity, and nutrient status. These systems are particularly relevant for precision irrigation and protected cultivation, supporting efficient resource management (Fu, X., & Akter, S. 2016).

AI-based advisory services analyze large datasets to provide predictive recommendations and diagnostic support. AI-powered image recognition can identify pests and diseases from photographs, offering expert-like

guidance for horticultural crops, though accuracy depends on data quality.(Klerkx & Rose, 2020; Geng et al.,2026)

Digital decision-support systems integrate multiple data sources—weather, soil, crop growth, sensors, and farmer records—to generate location- and crop-specific recommendations. Big-data technologies and Agriculture 4.0 innovations are reshaping extension into precision, data-driven systems (Wolfert et al., 2017; Klerkx et al., 2019).

Digital market and e-commerce platforms connect farmers directly with buyers, retailers, and consumers, improving access to price and demand information. This is particularly critical for perishable horticultural commodities, where timely marketing decisions are essential (Goyal, 2010).

Integrated digital platforms represent the latest stage of horticultural extension, combining multiple ICT tools into comprehensive digital ecosystems that support farmers throughout the production cycle. Systematic reviews highlight their potential to improve knowledge exchange, productivity, and profitability, although challenges such as poor connectivity, limited ICT skills, and insufficient training remain (Sen et al., 2025). The major ICT tools and digital platforms used in horticultural extension are summarized in Table 1, highlighting their applications in improving information dissemination, farmer advisory services, decision-making, and overall horticultural productivity.

Table 1. Major ICT Tools and Digital Platforms Used in Horticultural Extension

S. No.	ICT Tool / Technology	Major Application	Information / Service	Advantages	Key Reference
1	Mobile phones & SMS	Crop advisories	Weather, pest, fertilizer & market information	Low cost, wide reach	Fafchamps & Minten (2012); Fu & Akter (2016)
2	Smartphones & mobile apps	Digital advisory	Crop practices, disease, weather & markets	Personalized, interactive	Baumüller (2018); Fabregas et al. (2023)
3	Web portals	Online extension	Guides, videos, weather & market information	Accessible, information-rich	Klerkx et al. (2019); Spielman et al. (2021)
4	Social media	Farmer–expert interaction	Videos, photos & technical information	Interactive, peer learning	Nkoana & Zwane (2026)
5	Video-based extension	Practice demonstrations	Nursery, pruning, grafting & plant protection	Visual, repeatable learning	Zossou et al. (2009)
6	IVR	Voice advisory	Crop, weather & market information	Suitable for low-literacy users	Fabregas et al. (2023)
7	USSD services	Offline information access	Weather, prices & crop advice	Basic phones, low data requirement	Aker (2011); Fabregas et al. (2023)
8	GIS & GPS	Spatial advisory	Soil, crop suitability & pest mapping	Site-specific management	Klerkx et al. (2019)
9	Remote sensing	Crop monitoring	Crop stress, drought & vegetation indices	Large-area, timely monitoring	Wolfert et al. (2017)
10	Drones / UAVs	High-resolution monitoring	Crop health, canopy & disease detection	Rapid, precise assessment	Wolfert et al. (2017); Klerkx et al. (2019)
11	IoT	Real-time monitoring	Soil moisture, temperature & humidity	Automation, resource efficiency	Omar (2021); Wolfert et al. (2017)
12	AI & Machine Learning	Diagnosis & prediction	Disease detection, yield & risk prediction	Automated decision support	Klerkx et al. (2019); Lioutas et al. (2021)
13	Big Data Analytics	Data integration	Crop, soil, weather & market data	Predictive decision-making	Wolfert et al. (2017)
14	Digital DSS	Farm decisions	Irrigation, nutrients & pest management	Actionable recommendations	Klerkx et al. (2019); Lioutas et al. (2021)
15	Chatbots / AI assistants	Automated queries	Crop and pest-management advice	Fast, 24-hour support	Fabregas et al. (2023); Lioutas et al. (2021)
16	Digital markets	Market linkage	Prices, buyers &	Better market access	Goyal (2010);

	/ E-commerce		online sales		Lioutas et al. (2021)
17	Integrated digital platforms	Multi-channel extension	Advisory, weather, markets & learning	Comprehensive, scalable	Spielman et al. (2021); Porciello et al. (2022)
18	Cloud platforms	Data storage & integration	Farm, sensor & remote-sensing data	Accessible, scalable analysis	Wolfert et al. (2017); Klerkx et al. (2019)

4. Digital Extension and Technology Adoption among Horticultural Farmers

Digital extension has emerged as a vital mechanism for enhancing farmers' access to agricultural knowledge, technologies, and advisory services. Traditional extension systems often struggle with limited personnel, high costs, and geographical barriers, whereas digital platforms—such as mobile phones, smartphone applications, websites, social media, and videos—offer timely, location-specific, and farmer-centred information. This shift from one-way communication to interactive extension has created new opportunities for knowledge exchange, technology awareness, and improved decision-making (Spielman et al., 2021; Nkoana, P. M., & Zwane, E. M. 2026).

The effectiveness of digital extension in promoting technology adoption depends on the accessibility, relevance, and credibility of information. Digital advisory services provide guidance on improved varieties, nutrient management, irrigation, pest and disease control, weather, post-harvest handling, and market opportunities. Evidence shows that such interventions often lead to changes in farming practices and improved knowledge, though outcomes vary across technologies, farming systems, and local contexts (Digital Agriculture Services in Low- and Middle-Income Countries, 2022).

Mobile phones remain the most widely accessible digital tool, enabling farmers to receive information through SMS, voice calls, and mobile apps. These services reduce information gaps by offering timely recommendations, but their impact is shaped by farmers' digital literacy, connectivity, affordability, and ability to interpret messages (Fu & Akter, 2016; Baumüller, 2018). In horticulture, where crops are highly sensitive to weather, pests, and harvest timing, mobile advisories are particularly valuable. Studies highlight the importance of farmers' awareness of e-extension services and the need to address digital-literacy gaps before implementing interventions (Sahu et al., 2026).

Video-based extension has strengthened experiential learning by visually demonstrating complex horticultural practices such as grafting, pruning, canopy management, and post-harvest handling. Farmers often adapt and share digital content, making extension more participatory and context-specific (Fabregas et al., 2022). Similarly, social media platforms like WhatsApp and YouTube have created interactive spaces for farmers, extension agents, and researchers to exchange experiences and solutions. A systematic review found that perceived usefulness, digital literacy, internet access, credibility, and social influence are key factors shaping farmers' engagement with these platforms (Gouroubera et al., 2026).

Technology adoption through digital extension is influenced by socioeconomic, technological, institutional, and behavioural factors. Education, income, farm size, training, infrastructure, perceived usefulness, ease of use, and institutional support all play roles in shaping adoption decisions (Cui & Wang, 2023; Manzoor et al., 2025). Importantly, adoption is not a single event but a process involving awareness, interest, evaluation, trial, and continued use. Determinants of behavioural intention—such as perceived usefulness and social influence—may differ from those influencing actual usage, such as education, training, and farm characteristics (Dhakal, M., & Banerjee, M. 2026).

Interactive digital platforms further enhance adoption by enabling two-way communication, allowing farmers to submit questions, photos, and feedback, and receive tailored responses. These systems improve the relevance of advisories but face barriers such as poor connectivity, limited ICT skills, and insufficient training (Sen et al., 2025). Emerging directions include integrating digital extension with AI, IoT, remote sensing, and decision-support systems to deliver predictive, site-specific recommendations. While these technologies hold promise, their effectiveness depends on farmers' ability to interpret and apply complex information (Klerkx et al., 2019; Wolfert et al., 2017).

Overall, digital extension serves as a bridge between research institutions and horticultural farmers. Its greatest potential lies in complementing conventional extension with continuous information exchange, personalized advisories, participatory learning, and rapid feedback. Future strategies should adopt a farmer-centred approach, combining appropriate technologies with local-language content, digital-literacy training, human extension support, and reliable infrastructure (Spielman et al., 2021; Sen et al., 2025).

5. Digital Extension for Climate-Smart and Sustainable Horticultural Production

Climate change poses significant challenges to horticultural production, with rising temperatures, erratic rainfall, droughts, floods, heat waves, and emerging pests and diseases increasingly affecting crop performance. Given the sensitivity of horticultural crops to environmental fluctuations, farmers require timely, location-specific information to adapt their management practices. Extension and advisory services play a crucial role in promoting climate-smart agriculture by disseminating knowledge on adaptation strategies, resource conservation, and risk management (Billah et al., 2025).

Digital extension offers new opportunities to strengthen climate-smart horticulture by delivering real-time weather forecasts, crop advisories, and early-warning systems directly to farmers. Mobile applications, SMS,

voice services, and web platforms can provide information on rainfall probability, temperature, drought conditions, pest risks, and recommended practices, enabling farmers to adjust irrigation, fertilizer use, plant protection, and harvesting decisions in response to climatic conditions (Fu, X., & Akter, S. 2016).

Water management is a critical area where digital technologies can enhance sustainability. Tools such as soil-moisture sensors, IoT devices, weather stations, and digital irrigation systems support precision irrigation by integrating sensor data with decision-support systems. Reviews of digital horticulture highlight the potential of these technologies to improve water-use efficiency in crops like grapes, bananas, and tomatoes, thereby promoting resource-efficient production (Singh et al., 2025).

Remote sensing, GIS, and drone-based technologies further strengthen climate-risk assessment and crop monitoring. Satellite imagery and UAVs can detect canopy stress, nutrient deficiencies, and pest outbreaks before they become visible, supporting early intervention. These technologies are increasingly recognized as essential for climate adaptation and resilience in agriculture (Byamukama et al., 2025).

Artificial intelligence and machine learning add predictive capabilities to digital extension. By analyzing large datasets from sensors, satellites, and farm records, AI systems can forecast disease outbreaks, predict pest risks, estimate yields, and optimize irrigation schedules. The integration of AI with other digital tools shifts extension from reactive problem-solving toward proactive, predictive management (Klerkx et al., 2019; Singh et al., 2025).

Digital extension also promotes resource-efficient and environmentally sustainable practices. Farmers can access recommendations on integrated pest management, precision nutrient application, organic inputs, soil health, mulching, and climate-resilient varieties. These interventions reduce excessive agrochemical use and improve resource efficiency. Interactive digital services have been shown to enhance resilience and economic viability, though accessibility and information quality remain critical (Sen et al., 2025).

Early-warning systems delivered through digital platforms provide farmers with advance alerts about climatic hazards such as heavy rainfall, drought, or heat waves. This enables preventive action, including modifying irrigation schedules, postponing field operations, or adjusting fertilizer applications. Such timely information improves the quality of farm-level decisions and strengthens climate-risk management (Fu, X., & Akter, S. 2016; Billah et al., 2025).

In India, where smallholder farms are particularly vulnerable to climate variability, digitalization of climate-smart practices has shown promise in improving adaptation, mitigation, and productivity. Farmers' perceptions and adoption behavior, however, remain key determinants of success (2025). Beyond production, digital horticulture now extends to post-harvest management, traceability, and e-commerce, helping reduce losses and improve market connectivity (Singh et al., 2025).

Despite these opportunities, digital extension is not a standalone solution. Barriers such as poor connectivity, limited digital literacy, high costs, unreliable data, and inadequate technical support constrain adoption, especially among smallholders. Inclusive models that combine digital tools with conventional extension are therefore essential. Human extension agents can help interpret digital recommendations, validate information locally, and provide practical support during adoption, thereby improving trust and relevance (Billah et al., 2025; Spielman et al., 2021).

Digital extension represents a critical pathway for climate-smart and sustainable horticultural production. By integrating mobile advisories, remote sensing, GIS, IoT, AI, drones, and decision-support systems, farmers can access predictive, location-specific information to manage climatic and production risks. Future strategies should prioritize affordability, local-language content, digital literacy, reliable connectivity, and farmer participation to ensure that digital innovations contribute to equitable, resilient, and sustainable horticultural development (Vaishnavi et al., 2025; Sen et al., 2025). The role of digital technologies in strengthening climate-smart and sustainable horticultural production is illustrated in Figure 1, highlighting their potential contributions to improved resource-use efficiency, climate resilience, informed decision-making, and sustainable horticultural practices.



Figure 1. Role of digital technologies in strengthening climate-smart and sustainable horticultural production.

6. Digital Extension for Market Access, Value Chain Development and Income Enhancement in Horticulture

Digital technologies are increasingly reshaping agricultural marketing and value-chain systems by enhancing farmers' access to market information, buyers, financial services, logistics, and business opportunities. In horticulture, where commodities such as fruits, vegetables, flowers, and spices are highly perishable and vulnerable to price fluctuations, timely and reliable market information is critical. Digital platforms connect farmers with suppliers, traders, processors, retailers, and consumers, improving coordination and transparency across the value chain. Evidence suggests that these services expand farmers' access to markets and finance, though their long-term economic and environmental impacts remain less documented (Porciello et al., 2022).

Digital market information services provide real-time updates on commodity prices, demand, buyers, and trading opportunities. Such services reduce information asymmetry and strengthen farmers' bargaining power. Systematic reviews highlight that access to price and subsidy information is among the most common digital services, with income improvement being a key reported outcome (Porciello et al., 2022). Mobile phones and internet-enabled services remain the most accessible tools, enabling farmers to compare prices, negotiate transactions, and coordinate sales. ICTs have been shown to improve market participation, income opportunities, and access to financial services (Ma et al., 2023).

The rise of agricultural e-commerce platforms has further expanded direct marketing opportunities. Digital marketplaces allow farmers to advertise produce, receive orders, and organize delivery, shortening supply chains and reducing transaction costs. While e-commerce adoption may increase marketing costs, studies show that higher selling prices often outweigh these expenses, resulting in improved returns (Ma et al., 2023). Such mechanisms are particularly relevant for high-value horticultural commodities where quality differentiation and direct consumer engagement are advantageous.

Digital platforms also strengthen value-chain coordination by integrating production, harvesting, aggregation, transportation, storage, and marketing. This interconnectedness improves efficiency and responsiveness across the agri-food system (Krupitzer & Stein, 2024). Farmer Producer Organizations (FPOs), cooperatives, and producer groups benefit from digital tools that aggregate production data and market requirements, enabling collective bargaining and bulk marketing. Digitalization thus facilitates smallholder integration into formal and high-value markets, though connectivity, affordability, and literacy constraints remain significant challenges (Choruma et al., 2024).

Financial inclusion is another important dimension of digital extension. Platforms facilitate communication between farmers, financial institutions, and buyers, while digital records enhance transparency and trust. Studies show that digital systems can improve value-chain financing and cooperation, though effective governance and farmer inclusion are essential (Agyekumhene et al., 2018). Similarly, traceability technologies—such as QR codes, blockchain, and cloud databases—document production practices and supply-chain processes,

strengthening consumer confidence and supporting product differentiation, particularly for organic, certified, and export-oriented horticultural products (Krupitzer & Stein, 2024).

Digital extension also helps reduce post-harvest losses by improving coordination between production and markets. By aligning harvesting and distribution with buyer demand, farmers can minimize quality deterioration and mismatches between supply and demand. Social media platforms further expand marketing opportunities, allowing producers to promote fresh and processed products directly to consumers, build brand identity, and receive feedback. However, successful digital marketing requires complementary infrastructure such as reliable internet, packaging, transportation, payment systems, and consistent product quality (Choruma et al., 2024).

Despite these opportunities, barriers such as poor connectivity, high costs, limited literacy, and lack of trust in online transactions restrict participation by smallholders. Fragmentation and limited interoperability among platforms also pose challenges, and digitalisation risks reinforcing inequalities if larger agribusinesses adopt technologies more rapidly than resource-constrained farmers (Klerkx et al., 2019).

7.Challenges, Digital Divide and Barriers to Adoption of Digital Extension Services in Horticulture

Although digital and ICT-based extension services hold considerable promise, their effective use among horticultural farmers is hindered by a range of technological, economic, social, institutional, and behavioural constraints. The mere availability of digital platforms does not guarantee success; farmers must also have access to appropriate devices, reliable connectivity, relevant content, and the skills to use these tools effectively. Reviews of interactive digital extension highlight barriers such as poor internet connectivity, limited ICT knowledge, insufficient training, weak two-way interaction, and fragmented information networks (Sen et al., 2025). The major challenges and barriers affecting the adoption of digital and ICT-based agricultural extension services in horticulture are summarized in Table 2, highlighting the key constraints that need to be addressed to improve accessibility, adoption, and effective utilization of digital extension technologies.

Table 2. Major challenges and barriers affecting adoption of digital and ICT-based agricultural extension services in horticulture

S. No.	Major challenge / barrier	Effect on horticultural farmers	Possible strategies / interventions	Supporting references
1	Poor internet connectivity	Limits access to real-time advisories, videos, online markets, weather information and digital applications, particularly in remote horticultural areas.	Improve rural broadband, mobile network coverage and offline-enabled digital services.	Sen et al. (2025); Manzoor et al. (2025)
2	Limited digital literacy	Farmers may possess smartphones but lack the skills required to operate applications, interpret digital information and use online services effectively.	Conduct continuous digital-literacy and hands-on training programmes.	Sen et al. (2025); Xu et al. (2023)
3	High cost of devices and data	Smartphone, internet, subscription and technology costs may discourage small and marginal farmers from adopting digital services.	Develop affordable applications, subsidized connectivity and shared digital facilities through FPOs/KVKs.	Manzoor et al. (2025); Choruma et al. (2024)
4	Inadequate ICT infrastructure	Lack of electricity, network infrastructure and appropriate digital facilities restricts regular use of digital extension services.	Strengthen rural digital infrastructure and electricity availability.	Choruma et al. (2024); Sen et al. (2025)
5	Lack of technical knowledge	Farmers may not understand how to operate IoT devices, drones, sensors, digital platforms or decision-support systems.	Provide practical demonstrations, field schools and continuous technical support.	Sen et al. (2025); Khatri et al. (2024)
6	Language barriers	Digital advisories developed in technical or non-local languages may be difficult for farmers to understand and apply.	Develop multilingual, local-language and voice-based advisory systems.	Choruma et al. (2024); Manzoor et al. (2025)
7	Poor quality or unreliable information	Incorrect or generalized recommendations can result in inappropriate crop management, pesticide use or marketing decisions.	Integrate expert-validated information from agricultural universities, research institutions and extension agencies.	Sen et al. (2025)
8	Limited two-way interaction	One-way digital messaging may not adequately address location-specific pest, disease, nutrient or climate problems.	Develop interactive platforms, chatbots, expert consultation and farmer feedback mechanisms.	Sen et al. (2025)

9	Lack of centralized digital platforms	Farmers may need to use multiple applications for weather, crop advisory, market, finance and government services.	Develop integrated and interoperable digital extension platforms.	Sen et al. (2025); Khatri et al. (2024)
10	Age-related differences in adoption	Older farmers may have less exposure to smartphones, applications and advanced digital technologies.	Provide user-friendly interfaces, assisted digital services and peer-learning programmes.	Manzoor et al. (2025); Xu et al. (2023)
11	Gender and social inequalities	Unequal access to smartphones, internet, finance and training can limit participation of women and disadvantaged farmer groups.	Implement gender-sensitive training, affordable device access and inclusive digital programmes.	Choruma et al. (2024); Manzoor et al. (2025)
12	Lack of trust in digital information	Farmers may hesitate to act on information received through unfamiliar applications or social-media platforms.	Use trusted agricultural institutions, expert validation and transparent information sources.	Sen et al. (2025)
13	Data privacy and security concerns	Farmers may be reluctant to share farm, production, location and financial information through digital platforms.	Establish clear data ownership, privacy, consent and cybersecurity mechanisms.	Manzoor et al. (2025); Klerkx et al. (2019)
14	High investment in advanced technologies	Drones, IoT sensors, precision irrigation and AI-based systems may be unaffordable for individual smallholders.	Promote custom-hiring centres, FPO-based shared services and institutional support.	Manzoor et al. (2025); Khatri et al. (2024)
15	Limited institutional support	Weak coordination between extension agencies, research institutions, technology companies and farmers can reduce effectiveness.	Develop public-private partnerships and stronger institutional coordination.	Khatri et al. (2024); Sen et al. (2025)
16	Fragmented digital ecosystem	Incompatible applications and isolated databases can increase complexity and reduce usefulness to farmers.	Promote interoperability, common databases and integrated farmer-centric platforms.	Klerkx et al. (2019); Sen et al. (2025)
17	Resistance to technological change	Farmers accustomed to conventional practices may perceive digital technologies as risky or unnecessary.	Demonstrate economic benefits through field demonstrations, farmer champions and participatory approaches.	Manzoor et al. (2025)
18	Limited evidence of long-term impact	Short-term digital interventions may not demonstrate sustained improvements in productivity, income or sustainability.	Conduct long-term impact assessments, cost-benefit analysis and horticulture-specific studies.	Manzoor et al. (2025); Sen et al. (2025)

Digital Divide and Unequal Access

Unequal access to smartphones, internet services, electricity, affordable data, and digital skills creates disparities among farmers. Smallholders, resource-poor farmers, and those in remote areas are particularly disadvantaged. Socioeconomic factors such as age, education, gender, and income also influence adoption, with better-educated and wealthier farmers more likely to embrace digital technologies (Amoussouhoui et al., 2024; Choruma et al., 2024).

Digital Literacy and Skills

Digital literacy is critical for interpreting and applying information from digital platforms. Farmers may own smartphones but lack the ability to evaluate information credibility or use specialized applications. Extension personnel also require training in mobile apps, digital content creation, data analysis, and AI-based advisory systems to ensure that digital tools complement rather than replace human extension (Xu et al., 2023; Khatri et al., 2024).

Connectivity and Infrastructure

Weak network coverage, unstable internet, and inadequate electricity infrastructure limit the effectiveness of digital extension, especially when farmers need real-time information on weather, pests, or markets. In horticulture, where decisions are time-sensitive, delays can undermine advisory effectiveness. Complementary offline mechanisms such as SMS, voice messages, and IVR remain essential (Choruma et al., 2024).

Cost and Affordability

High costs of smartphones, data services, and advanced technologies like IoT sensors, drones, and automated irrigation systems restrict adoption among smallholders. Financial constraints are a major barrier in low- and

middle-income countries. Affordable, scalable services and shared-access models through cooperatives or FPOs can help reduce costs (Manzoor et al., 2025).

Quality and Relevance of Information

The rapid growth of digital platforms has led to an abundance of agricultural information, but not all of it is reliable or locally relevant. Conflicting recommendations from social media or commercial apps can confuse farmers. For horticulture, location-specific advisories are essential, requiring integration of validated data from universities, research institutions, and meteorological agencies (Sen et al., 2025).

Language and Local Context

Language barriers limit comprehension, as many platforms are developed in English or other non-local languages. Farmers often prefer regional languages and simple communication formats. Localized content, audio-visual tools, and voice-based systems can improve accessibility (Khan, 2025).

Trust, Privacy, and Data Security

Concerns about data ownership, privacy, and commercial use affect farmers' willingness to share information. Transparent governance policies on data collection, access, and protection are necessary to build trust (Klerkx et al., 2019).

Limited Two-Way Interaction

Many digital platforms still function as one-way information delivery systems. Farmers often lack opportunities to ask questions or provide feedback. Interactive tools such as chatbots, IVR, and expert consultations can improve relevance, but must be supported by agricultural experts to ensure scientific accuracy (Sen et al., 2025).

Behavioural and Socio-economic Barriers

Farmers' perceptions of usefulness, risk, and ease of use, along with social influence and prior experience, shape adoption decisions. Older farmers or those with limited exposure may require more training and support, though user-friendly designs can mitigate these barriers (Amoussouhoui et al., 2024; Manzoor et al., 2025).

Gender and Social Inclusion

Women farmers often face greater barriers due to limited access to devices, internet, financial resources, and training opportunities. Gender-sensitive approaches, including affordable access, women-focused training, and inclusive farmer groups, are essential to ensure equitable participation (Choruma et al., 2024).

Fragmentation of Platforms

Farmers frequently need to use multiple applications for weather, crop advisories, markets, and finance, creating complexity and reducing adoption. Integrated platforms that combine advisory, market, financial, and government services are needed to reduce fragmentation and build farmer-centred ecosystems (Khatri et al., 2024).

Strategies for Inclusive Digital Extension

Addressing these challenges requires coordinated efforts among farmers, extension agencies, universities, governments, private technology providers, and farmer organizations. Strengthening infrastructure, building farmer capacity, developing localized content, and ensuring institutional support are critical. Meta-analyses show that digital interventions can improve input adoption, yields, and incomes, but evidence remains geographically concentrated (Beach et al., 2025). Future research should focus on long-term impacts, inclusiveness, and crop-specific outcomes in horticulture.

8. Future Prospects and Emerging Trends in Digital and ICT-Based Horticultural Extension

The future of horticultural extension will be shaped by advanced digital technologies such as artificial intelligence (AI), the Internet of Things (IoT), remote sensing, drones, big data analytics, robotics, blockchain, digital twins, and decision-support systems. These innovations are transforming extension from conventional information delivery into predictive, interactive, and personalized advisory services. Scholars highlight that Agriculture 4.0, characterized by interconnected sensors, cloud computing, and automation, is redefining agricultural production and knowledge systems (Klerkx et al., 2019; Wolfert et al., 2017; Klerkx & Rose, 2020). Recent studies also show that adoption of digital technologies depends on socioeconomic, institutional, and behavioural factors, underscoring the need for integration with conventional extension approaches (Manzoor et al., 2025).

Artificial Intelligence and Personalized Advisory

AI is expected to play a central role in horticultural extension by analysing large datasets from sensors, satellites, and farm records to generate crop-specific recommendations. Applications include pest and disease diagnosis, irrigation scheduling, nutrient management, and yield forecasting. AI integration with IoT and remote sensing is already enabling smart crop management, moving extension towards personalized, location-specific advisories (Mishra et al., 2025; Xu et al., 2023).

IoT and Real-Time Monitoring

IoT devices such as soil-moisture sensors, weather stations, and humidity monitors provide continuous data for real-time crop monitoring. These systems support precision irrigation and nutrient management, replacing periodic extension visits with continuous, responsive advisory services (Wolfert et al., 2017; Klerkx et al., 2019).

Remote Sensing, Drones, and Precision Horticulture

Satellite imagery and UAVs offer high-resolution monitoring of crop stress, nutrient deficiencies, and pest outbreaks. Combined with AI and GIS, these tools enable site-specific recommendations and precision management in horticulture (Bhanusree et al., 2023; Mishra et al., 2025).

Big Data and Predictive Analytics

The expansion of digital agriculture generates vast datasets that can be transformed into predictive insights. Big-data analytics can forecast yields, pest outbreaks, irrigation needs, and market demand, shifting extension from reactive to preventive approaches (Wolfert et al., 2017; Manzoor et al., 2025).

Digital Twins and Simulation

Digital twins create virtual models of farms or greenhouses, allowing simulation of alternative management scenarios before implementation. Their integration with IoT and AI could provide powerful tools for scenario-based extension (Klerkx et al., 2019; Klerkx & Rose, 2020).

Blockchain and Traceability

Blockchain technologies can improve transparency and traceability in horticultural value chains, particularly for organic and export-oriented products. They document production practices and supply-chain processes, enhancing consumer confidence while raising questions of data governance and equity (Kos & Kloppenburg, 2019).

Generative AI and Conversational Advisory

Conversational AI tools can provide interactive, natural-language responses to farmers' queries on crop management and markets. While promising for accessibility, expert validation remains essential to avoid misinformation (Xu et al., 2023; Klerkx & Rose, 2020).

Robotics and Automation

Robotics will increasingly support labour-intensive horticultural operations such as harvesting, spraying, and grading. Extension services will play a role in guiding farmers on feasibility, safety, and economic suitability of these technologies (Klerkx et al., 2019).

Integrated Digital Ecosystems

Future extension systems will likely evolve into integrated platforms combining weather forecasts, crop advisories, pest diagnosis, market intelligence, financial services, and government schemes. Such ecosystems can reduce fragmentation and provide comprehensive decision support (Porciello et al., 2022; Sen et al., 2025).

Climate-Smart Digital Extension

Digital tools such as AI-based forecasting, IoT irrigation systems, and early-warning platforms can strengthen climate resilience in horticulture. They support adaptation to drought, heat stress, and pest risks while promoting resource-efficient practices (Billah et al., 2025; Vaishnavi et al., 2025).

Farmer-Centred and Participatory Approaches

Future extension must remain farmer-centred, recognizing diversity in resources, literacy, and production systems. Participatory development involving farmers, researchers, and technology providers can improve relevance and usability (Coggins et al., 2022; Sen et al., 2025).

Responsible and Inclusive Digital Agriculture

Issues of data ownership, privacy, cybersecurity, and unequal access must be addressed to ensure inclusivity. Responsible innovation and transparent governance are essential to prevent widening inequalities (Klerkx et al., 2019; Kos & Kloppenburg, 2019).

Future Research Directions

Research should evaluate the effectiveness, scalability, and sustainability of emerging technologies such as AI, IoT, drones, and digital marketplaces. Evidence from recent meta-analyses shows that adoption determinants vary by region, crop, and farmer characteristics, highlighting the need for interdisciplinary approaches (Xu et al., 2026; Geng et al., 2026).

9. Policy Recommendations and Institutional Strategies for Strengthening Digital and ICT-Based Horticultural Extension

Transforming horticultural extension through digital and ICT-based technologies requires more than technological innovation—it demands supportive policies, institutional coordination, infrastructure development, and farmer-centred implementation. Digital extension should be viewed as an integrated system involving farmers, extension agents, research institutions, government agencies, private technology providers, and farmer organizations. Studies highlight that infrastructure, training, knowledge, and interactive communication are critical for effectiveness (Sen et al., 2025; Manzoor et al., 2025). Evidence from horticulture-specific meta-analyses further shows that adoption determinants vary across willingness, behavioural intention, and actual usage, with infrastructure, training, social networks, and institutional support being particularly influential (Geng et al., 2026). The proposed digital extension policy framework for horticultural development (Figure 2) emphasizes the integration of these technological, institutional, infrastructural, and farmer-centred components to promote effective digital extension services and sustainable horticultural development.

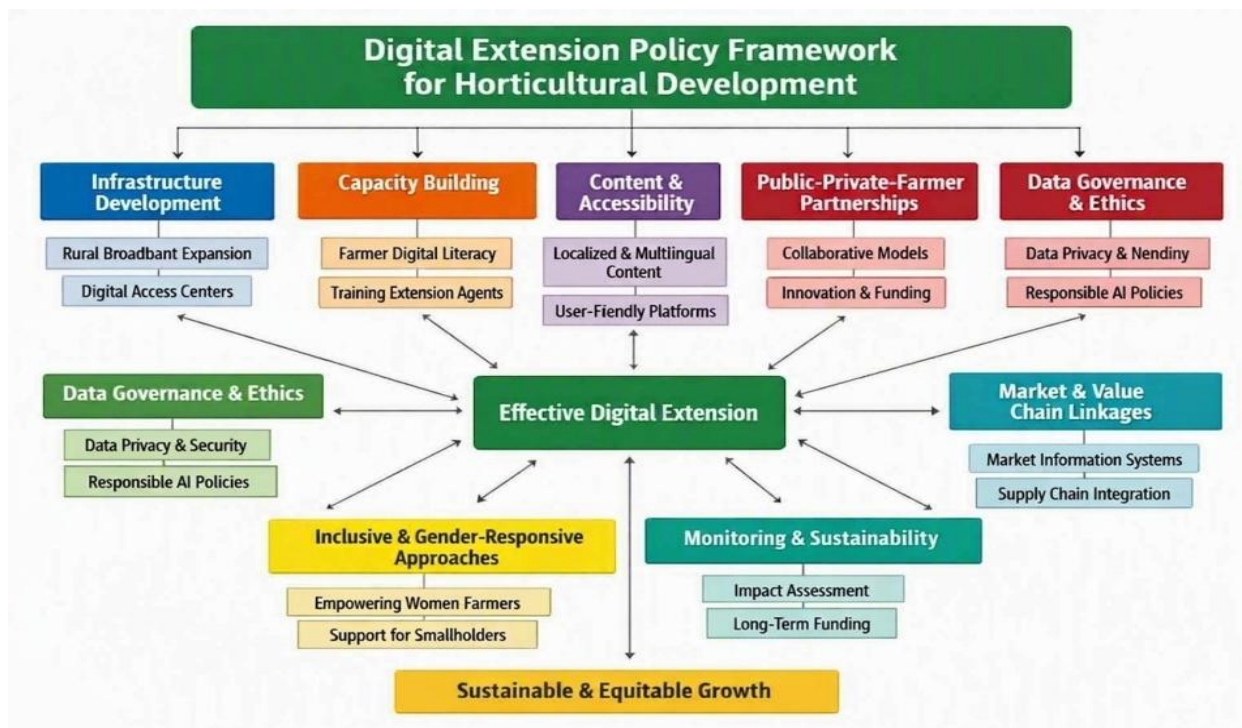


Figure: 2 Digital Extension policy Frame work for Horticultural Development

Strengthening Rural Digital Infrastructure

Reliable internet, mobile networks, and affordable services are essential for digital extension. Poor connectivity in rural horticultural regions restricts access to mobile apps, online markets, and real-time advisories. Investment in rural broadband, mobile coverage, and community digital centres should be prioritized (Sen et al., 2025; Manzoor et al., 2025).

Improving Digital Literacy and Farmer Capacity

Digital literacy is fundamental for farmers to interpret and apply digital information. Training should cover smartphone use, evaluating information credibility, and applying digital advisories in practice. Continuous training through farmer field schools and demonstrations is recommended (Xu et al., 2026; Geng et al., 2026).

Developing Farmer-Centric and Multilingual Platforms

Platforms must be tailored to farmers' needs, languages, and production contexts. Generic advisories often lack relevance. Multilingual, crop-specific, and location-specific content delivered via text, audio, video, and voice interfaces can improve usability (Coggins et al., 2022; Sen et al., 2025).

Integrating Digital with Public Extension

Digital platforms should complement—not replace—conventional extension. Extension officers and scientists can validate digital information and contextualize recommendations. Hybrid models combining digital delivery with field-level expertise are essential (Xu et al., 2023; Khan, 2025).

Strengthening Public–Private–Farmer Partnerships

Collaboration among government, universities, agri-tech firms, FPOs, and farmers is vital. Public institutions provide validation and policy support, while private actors contribute innovation. Partnerships ensure services remain reliable, affordable, and accessible (Klerkx et al., 2019; Manzoor et al., 2025).

Data Governance and Responsible AI

Policies must address data ownership, privacy, consent, and responsible use of AI. Transparent governance frameworks are needed to ensure farmers retain control over their data while benefiting from digital innovations (Klerkx & Rose, 2020; Kos & Kloppenburg, 2019).

Gender-Responsive and Inclusive Extension

Women, elderly, and marginal farmers often face greater barriers to digital adoption. Gender-sensitive policies should provide affordable devices, targeted training, and inclusive participation in digital farmer groups (Manzoor et al., 2025; Geng et al., 2026).

Strengthening Market and Value-Chain Linkages

Digital extension should integrate production advice with market intelligence, logistics, and postharvest management. Interoperable platforms linking farmers with suppliers, markets, and financial institutions can improve decision-making and transparency (Porciello et al., 2022; Krupitzer & Stein, 2024).

Capacity Building of Extension Personnel

Extension workers require training in AI, IoT, GIS, drones, and data analytics to interpret and validate digital outputs. Continuous professional development is necessary to ensure effective integration of digital tools (Sen et al., 2025; Xu et al., 2023).

Integrated and Interoperable Platforms

Fragmentation across multiple apps reduces usability. Integrated platforms combining weather, pest alerts, crop advisories, market information, and financial services can provide comprehensive support (Porciello et al., 2022; Choruma et al., 2024).

Monitoring and Evaluation

Digital extension programmes should be systematically evaluated for impacts on adoption, productivity, income, and resilience. Baseline assessments, longitudinal studies, and multi-dimensional indicators are needed (Beach et al., 2025; Geng et al., 2026).

Sustainable Financing

Long-term financing is essential to maintain platforms, update databases, and train users. Public investment, institutional funding, and public–private partnerships should be prioritized to ensure sustainability (Porciello et al., 2022; Sen et al., 2025).

Hybrid Extension Models

Face-to-face interaction remains critical for complex horticultural practices. Digital tools should complement—not replace—personalized extension support, ensuring both scalability and contextual relevance (Coggins et al., 2022; Sen et al., 2025).

Policy Priorities for India

India's digital horticulture strategy should emphasize affordable connectivity, multilingual advisories, integration of ICAR and SAU expertise, strengthening of Krishi Vigyan Kendras and FPOs, and interoperable platforms. Policies must consider differences in farmers' education, training, networks, and crop systems (Sahu et al., 2026; Singh et al., 2025; Geng et al., 2026).

10. Conclusion and Future Research Directions for Digital and ICT-Based Horticultural Extension

Digital and ICT-based extension services have become integral to modern horticultural development. The integration of smartphones, mobile apps, internet platforms, remote sensing, IoT devices, AI, drones, big-data analytics, and digital marketplaces is revolutionizing how horticultural knowledge is created and shared. These technologies enhance the timeliness, accessibility, and relevance of advisory information, supporting farmers in decisions related to crop management, pest and disease control, irrigation, nutrient application, harvesting, and marketing. Evidence shows that digital interventions can improve input adoption, yields, and income, though outcomes vary by context and technology (Beach et al., 2025; Porciello et al., 2022).

Overall Impact on Horticulture

Digital extension has broadened the reach of traditional advisory systems, overcoming spatial and time constraints. Mobile advisories, social media, online communities, videos, and interactive platforms provide timely support during critical crop stages. The most effective systems combine technology with human expertise, local knowledge, and farmer feedback (Coggins et al., 2022; Sen et al., 2025). Horticulture, being high-value and knowledge-intensive, is particularly suited for digital transformation. Studies confirm that adoption of Horticulture 4.0 technologies depends on technical, social, infrastructural, and institutional factors, highlighting the need for holistic approaches (Geng et al., 2026).

Contribution to Technology Adoption and Productivity

Digital extension accelerates adoption of improved technologies such as precision irrigation, integrated pest management, protected cultivation, and post-harvest innovations. By bridging information gaps, it promotes informed decision-making and productivity gains. Meta-analyses show positive effects on input adoption and income (Beach et al., 2025). However, adoption is a multi-stage process—from awareness and willingness to behavioural intention and sustained use—each influenced by distinct socioeconomic and institutional factors (Geng et al., 2026). Extension programmes should therefore address these stages separately.

Role in Climate-Smart and Sustainable Development

Digital tools support climate-smart horticulture by providing weather forecasts, early warnings, and resource-use recommendations. They enhance adaptation and resilience to droughts, heatwaves, and pest outbreaks (Billah et al., 2025; Manzoor et al., 2025). Sensor-based irrigation and AI-driven decision systems enable efficient water and nutrient management, improving profitability and sustainability (Singh et al., 2025).

Emerging Opportunities from Advanced Technologies

The convergence of AI, IoT, remote sensing, drones, and cloud computing is creating more precise and responsive extension systems. AI can process complex datasets for personalized recommendations, while IoT sensors and drones enable continuous monitoring of crop conditions (Klerkx et al., 2019; Wolfert et al., 2017). Digital twins—virtual models of farms or greenhouses—offer simulation-based decision support, allowing farmers to test management strategies before implementation (Singh et al., 2025).

Research Gaps and Priorities

Despite rapid progress, long-term evidence on sustained behavioural and productivity impacts remains limited. Most studies focus on short-term knowledge or practice changes rather than enduring economic or environmental outcomes (Porciello et al., 2022). Future research should adopt longitudinal and comparative designs to assess durability, frequency, and scalability of digital interventions. Integrated models that consider socioeconomic, technological, and behavioural dimensions are needed (Manzoor et al., 2025). Horticulture-specific studies should explore diverse crop systems, farm sizes, and regional contexts, as adoption determinants vary by crop and technology (Geng et al., 2026).

Towards an Integrated Human–Digital Extension System

The future lies in hybrid systems combining digital tools with human expertise. Digital platforms can deliver scalable information, while extension professionals provide contextual interpretation and trust-based support. Evidence shows that participatory learning combined with digital tools enhances effectiveness (Ongachi et al., 2026). A successful system should be farmer-centred, multilingual, inclusive, affordable, and interactive, enabling two-way communication and collaboration among farmers, universities, research stations, and technology providers (Sen et al., 2025; Coggins et al., 2022).

Future Research Directions for India

In India, research should focus on integrated digital systems linking farmers with universities, Krishi Vigyan Kendras, FPOs, and private advisory services. Priorities include multilingual AI-based advisories, localized weather and pest alerts, and digital platforms integrating production and marketing information (Singh et al., 2025; Sahu et al., 2026). Evaluation should use measurable indicators—adoption, productivity, profitability, resource efficiency, resilience, and inclusiveness—and assess whether services reach smallholders, women, and elderly farmers (Manzoor et al., 2025; Xu et al., 2026).

CONCLUSION

Digital and ICT-based extension offers transformative potential for horticulture, enabling timely, personalized, and data-driven decision-making. Yet, success depends on infrastructure, literacy, affordability, trust, and institutional capacity. The future will be defined by a human–digital partnership, where technology enhances rather than replaces extension professionals. A farmer-centred, participatory, and evidence-based approach integrating digital innovation with local knowledge and institutional support will drive productive, profitable, and climate-resilient horticultural development. The ultimate goal is to build an inclusive, intelligent extension ecosystem that delivers the right information to the right farmer at the right time.

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Consent for publication

All authors consent the publication of the current article.

Competing interests

The authors declare no competing interests.

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