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Digital technologies to accelerate the impact of climate smart agriculture by next-generation farmers in Africa

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The adoption of digital technologies for scaling Climate-Smart Agriculture (CSA) practices can enhance agricultural productivity, food security, and livelihood sustainability of smallholder farmer communities in Africa. While digital agronomy supports for smallholder farmers present significant opportunities for strengthening agricultural extension systems, there are also significant barriers faced by smallholders in accessing and using digital agronomy services. Despite the rapid growth in phone and internet access in Africa, many smallholder farming communities and households lack effective access to the phone and internet services necessary for effective digital agronomy delivery. The digital divide that constrains smallholder farmers acts as a brake on the ambitions and targets for CSA scaling and for agricultural sector development across Africa, including in the Comprehensive Africa Agriculture Development Programme (CAADP) held in Strategy and Action Plan, and the Kampala CAADP Declaration on Building Resilient and Sustainable Agrifood Systems in Africa. Currently, there are a broad range of digital technologies (e.g., radio, mobile phone apps, video, mobile phone apps, animations, and social media platforms) that can be harnessed for scaling CSA amongst smallholder farmers, with a rapidly growing number of digital agronomy developers and providers. However, the affordability of phone and internet services for poorer smallholders, in addition to lack of technology infrastructure and digital literacy skills, remains a barrier to "last mile" delivery of effective digital agronomy services. As digital access becomes more affordable and digital agronomy systems become more powerful, pervasive (e.g., via social media and peer-to-peer training approaches) and localized (e.g., using artificial intelligence and machine translation), there is significant potential for digital agronomy systems to augment and strengthen national agricultural extension systems supporting smallholder farmers. In particular, digital agronomy services can help accelerate scaling of Climate-Smart Agriculture (CSA) practices for the millions of smallholder farmers who are most vulnerable to the unfolding climate crisis affecting their farming systems and livelihoods.

KEYWORDS
climate smart agriculture, extension services, peer-to-peer training, young farmers, digital technologies, Sub-Saharan Africa

Introduction

Digital technologies can enable positive transformations of agricultural and food systems through scaling of climate smart agriculture (CSA) practices that can support smallholder farmers to achieve improved food security, nutrition, resilience, and livelihoods across Africa (Lipper et al., 2014; Dhehibi et al., 2020; Zougmoré et al., 2021). Digital technologies can be defined as tools or devices that can access, process, store and relay data for functional outcomes (Berger et al., 2018; Coggins et al., 2022). Digital technologies encompass hardware (e.g., phones, TV, computers), software (e.g., apps, dashboards), internet databases, social networks and decision-support tools (Evans, 2018; Balogun et al., 2020). Digital technologies can connect a diverse group of people such as farmers, extension workers, organizations, and government to better collaborate, network, communicate and gather information about the agricultural and food sector, for example details on prices, markets, inputs, customers, and products (Davis et al., 2018; Owiti et al., 2023). In principle, digital technologies can play a useful role in enabling CSA practices to be implemented more widely and efficiently (Abegunde et al., 2019; Kurgat et al., 2020).

Social media platforms offer a range of diverse functionalities such as socializing on Facebook, learning via YouTube, job opportunities on LinkedIn, and shopping via eBay. Capacity building for farmers using technologies such as the internet, computers, mobile phones, social media, videos and animations, and other digital platforms is widely promoted as an emerging means for improved and more cost-effective information delivery and feedback systems with farmers (Ajayi and Fapojuwo, 2014). For instance, participatory video training has helped farmers and extension teams in Ethiopia to better interact through shared discussion of videos related to agriculture (Gandhi et al., 2009; Abate et al., 2019).

YouTube channels delivered by digital agronomy providers such as Digital Green and Access Agriculture provide learning latforms for farmers to gain access to training videos and to publish their own videos on agricultural practices. Due to its widespread adoption and use, YouTube may have significant potential for curation and dissemination of agricultural videos (Alföldi et al., 2019), where there is either significant bandwidth and/or equipment available for routine access. Jellason et al. (2021) have highlighted that mobile payment applications including M-Pesa, M-Farm, and Esoko provide access to financial services and market data to farmers e.g., in Tanzania, Kenya, Ghana, and South Africa. Such payment applications help farmers perform mobile money transactions for services and products, acquire market prices via Short Message Services (SMS), and access weather information.

A 20 year study (across 44 countries) of the effects of digital infrastructure on inclusive growth in Sub-Saharan Africa over 20 years, indicated that digital infrastructure enhances inclusive growth across countries of all income levels (Kouladoum, 2023). Digitization and digital technologies can help bridge gaps that exist in extension systems, which generally suffer from constraints such as staff, resources and financing. It is widely considered that ongoing advances in digital technologies can help agri-food systems to become more climate-smart through more effective information dissemination to farmers and other food system stakeholders (Bahn et al., 2021). The ongoing evolution of different mobile phone applications is facilitating multiple important services to farmers, including money transactions, access to marketing information, and weather forecasting updates. In addition, there are efforts to digitalize government social protection schemes which also reach farming households and rural communities (Ncube et al., 2023). It is becoming clear that there is a crucial role for Artificial Intelligence (AI) to play in scaling agricultural advisory and extension services to accelerate delivery of actionable advice directly to smallholder farmers. Through hyper-localized AI-driven tools, context-specific information can be delivered at scale to improve the adoption of CSA, while incorporating weather predictions, soil analysis and crop health diagnostics to maintain optimal farm productivity (Mmbando, 2025).

Several studies have highlighted the expansion of digital technology in Sub-Saharan Africa (Lohento and Ajilore, 2015; Misaki et al., 2018; Kudama et al., 2021). By the end of 2018, when the overall population of Sub-Saharan Africa was 1.03 billion people, there were 456 million mobile subscribers in the region, of which 239 million people were regularly accessing an Internet connection (Omulo and Kumeh, 2020). Circa 60% of smallholder farmers in Sub-Saharan Africa have been reported to have access to mobile connections (Jellason et al., 2021).

Despite the advancement of digital technologies, the accessibility of digital information for poorer citizens is still a challenge in many parts of Africa, particularly in Sub-Saharan Africa (Jellason et al., 2021). Due to the digital divide, which is increasingly a bandwidth divide, richer users tend to benefit more from advanced digital technologies than poorer users (Chang et al., 2020; Cariolle, 2021). When compared to richer counterparts, poorer farmers typically have less access to digital technologies and internet services that require higher (including cost) bandwidth, making it currently more difficult for smallholder farmers to access digitally delivered extensive services (Mushi et al., 2022). Limited access to digital services is influenced by a range of factors, including poor infrastructure and illiteracy, combined with financial, political, and cultural barriers (Aruleba and Jere, 2022). Overcoming such access barriers requires farmers' organizations, government, and other stakeholders to combine efforts to ensure greater access to digital tools for poorer smallholders and rural households (Tadesse and Bahiigwa, 2015; Sousa et al., 2019).

In this review, the potential of digital technologies for scaling climate-smart agriculture among next-generation farmers (i.e., current and future young farmers) is reviewed. Our objective is to review the potential, opportunities and challenges for scaling of CSA practices through a wide range of digital technologies and communication channels.

The growth of digital communication technologies in Sub-Saharan Africa

While it remains the least connected global region, Sub-Saharan Africa has experienced consistent increases in internet usage over the past decades (Odhiambo, 2022). The rapid expansion of mobile broadband has been one of the features of such increases (Cariolle, 2018). For instance, the International Telecommunications Union (ITU) World Telecommunications/ICT Indicators database indicates that the number of mobile cellular subscriptions per 100 people in Sub-Saharan Africa rose from 2 in 2000 to 89 in 2023. The rate of increase in broadband connectivity influences the number of people using digital devices (e.g., mobile phones) to gain more access to information through applications, channels, and platforms. The Global System for Mobile Communications (GSMA, 2021) organization has estimated that there will be an increase to 615 million people who are unique mobile subscribers in Sub-Saharan Africa by 2025.

Figure 1 compares the changes over time in digital technology access and adoption in Sub-Saharan Africa, compared to other regions (Figures 1A–C). While the number of individuals using the internet is increasing slowly over time in Sub-Saharan Africa (Figure 1A), the proportion of individuals using the internet remains lowest relative to the majority of other regions globally (Figure 1B). Also, while Sub-Saharan Africa has the lowest % levels of fixed telephone subscriptions (Figure 1C), the % levels of

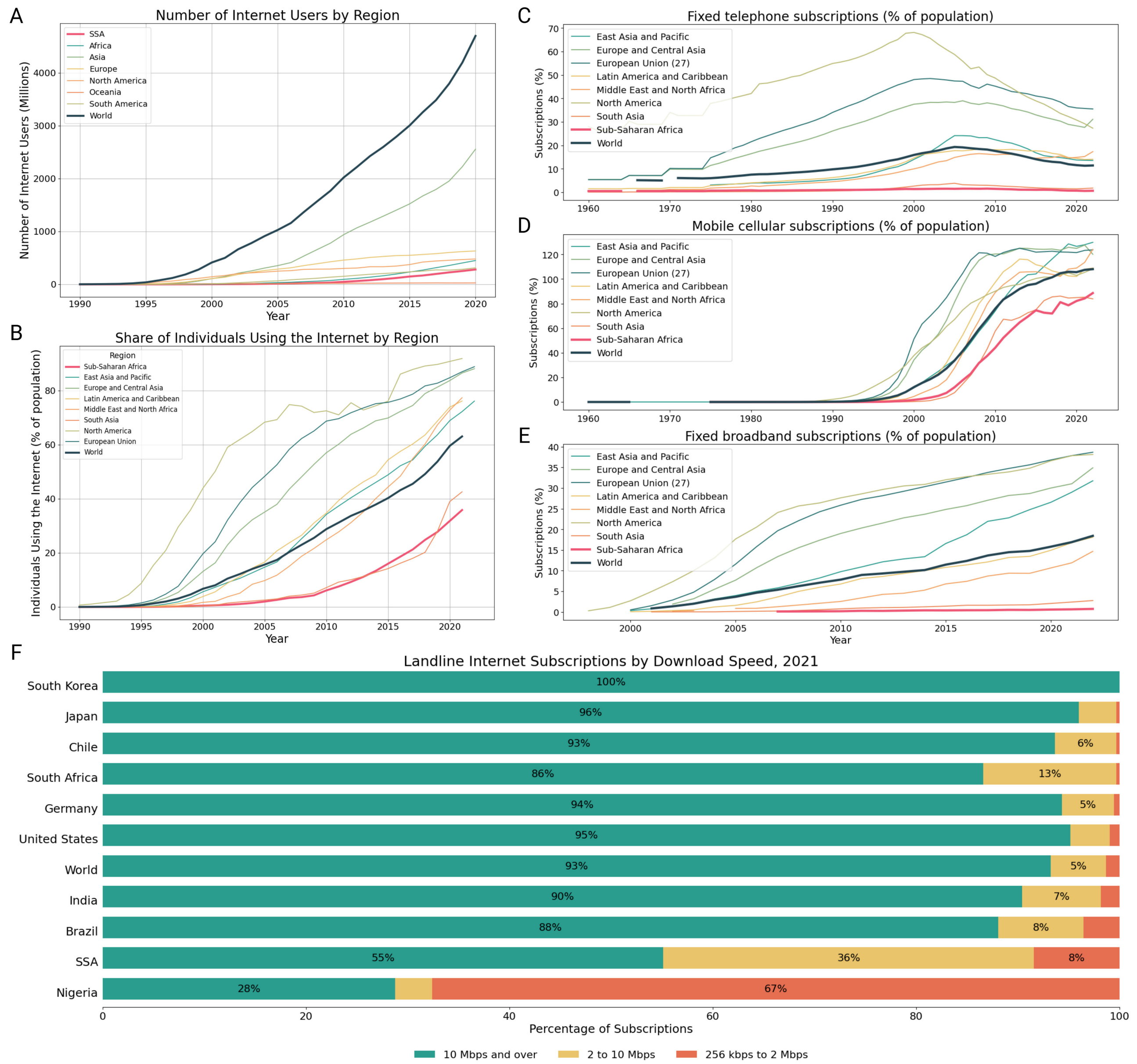

FIGURE 1
Trends in Internet and Internet & Communication Technologies (ICT) usage in sub-Saharan Africa, relative to other regions. **(A)** Number of internet users (millions); **(B)** percentage of individuals using the internet; **(C)** percentage of population with fixed telephone subscriptions; **(D)** percentage of population with mobile cellular subscriptions; **(E)** percentage of population with fixed broadband subscriptions; **(F)** landline internet subscriptions by download speed (2021), for selected countries. Source: Our World in Data.

mobile cellular subscriptions in the region are relatively high and comparable to other regions (Figure 1D). Despite the likelihood that poorer households and communities will have the least access to mobile cellular technology, the high rates of mobile cellular subscriptions could represent an opportunity for reaching larger numbers of smallholder farming communities in Sub-Saharan Africa (Figure 1C). However, despite high rates of mobile cellular subscriptions in Sub-Saharan Africa, one of the challenges for digital advisory services to reach smallholders is the internet bandwidth (i.e., the bit rate = number of bits per second) which can limit the types of content (e.g., large files or video content) that can be accessible to smallholder communities in Sub-Saharan Africa (Figure 1F).

Despite the increased adoption of digital technologies by farmers, and their potential for addressing challenges such as climate change, sustainability and market linkages, the digital divide between richer and poorer farming households remains a barrier (Cariolle, 2018; Alper and Miktus, 2019). A digital divide in farming exists when large-scale farmers have access to internet services while poorer farmers lack access (Mutula, 2021). Yet, improvement in digital connectedness for poorer smallholder households in Sub-Saharan Africa could lead to greater participation in value chains (Cariolle and Da Piedade, 2023). Ultimately, the digital divide has shifted from simple access to the internet to the bandwidth divide between those who can afford the charges for more bits per second and high-speed internet services (Hilbert, 2016). There are some efforts underway to bridge the digital divide gap—for instance the Vodacom Foundation has trained 600 women smallholder farmers in digital literacy to enable their participation in the digital agricultural value chain in Limpopo and KwaZulu, South Africa.

Internet expansion amongst younger populations is occurring quickly, where 99% of Vijabiz youth groups in Kenya use mobile phones (and 29% use computers) to access the internet (Wahiu et al., 2020). Also, mobile money (M-PESA) applications are widely used for mobile transactions and as spreadsheet for record keeping. However, the youth empowerment initiative Vijabiz faced challenges such as the cost of ICT devices, internet subscription, and poor and unreliable connectivity where the project was implemented.

In principle, digital technologies can play a crucial part in supporting the dissemination and scaling of climate-smart agriculture practices in Sub-Saharan Africa (Newell et al., 2019; Ryoya and Steensland, 2021). Any such scaling needs to consider the changing age structures of farmers, where a focus on enabling digital technology access for younger farmers can be important for transitions to more climate-smart agricultural systems. The policy environment for digital technologies can play a key role in enabling broader access to digital technologies and digital agronomy services, especially for poorer smallholders, including women and youth (Munga, 2022). For instance, policy options can include increasing access to digital services and tools through national extension systems, financial credits, agricultural subsidy programs, investing in improving the technical skills of farmers, and reducing costs of delivery through lower taxes on service providers.

Portfolio approach to scaling of climate smart agriculture practices and technologies

Climate Smart Agriculture (CSA) is an integrated approach for sustainably managing agricultural systems—including croplands, livestock, forests, and fisheries—to enhance food security while addressing the impacts of climate change (Lipper et al., 2014; Rosenstock et al., 2016; Vishnoi and Goel, 2024). CSA is grounded in conventional agricultural knowledge and sustainability frameworks, and is uniquely oriented toward confronting climate challenges within food systems. It integrates diverse, site-specific practices—ranging from climate-resilient crops and conservation tillage to agroforestry, precision agriculture, water efficiency, and enhanced livestock systems—while systematically balancing the goals of productivity, adaptation, and mitigation (Lipper et al., 2014; Ma and Rahut, 2024).

CSA has the potential for significant agricultural transformation in Sub-Saharan Africa due to the low productivity of agriculture, high levels of climate vulnerability and the high reliance of the populations in most countries in the region on agriculture for their livelihoods (Jayne and Sanchez, 2021; Ofori et al., 2021). The scaling of different portfolios of CSA practices tailored to different farmers' needs and the needs of their farming systems is considered important for reducing the threats by increasing farmers' adaptive capacity and resilience to climate change impacts (Lipper et al., 2014; Makate, 2019; Ma and Rahut, 2024).

CSA typically provides a basket of options to improve farming and livelihood systems through the use of water, nutrient, carbon, energy, weather and knowledge-sharing technologies and techniques (Rosenstock et al., 2016; Suleman, 2017). With 80% of farmers in Sub-Saharan Africa considered vulnerable to climate change, a wide portfolio of CSA interventions have been identified, including rainwater harvesting, irrigation, crop diversification, index-based insurance, stress-tolerant crops and varieties, agroforestry, use of zero tillage, residue management and improved livestock management (Rosenstock et al., 2016; Ma and Rahut, 2024). Through increasing access of smallholders to "bundles" of CSA interventions, smallholder resilience to climatic stresses is expected to be strengthened (Abegunde et al., 2019; Jones et al., 2023).

The rapid and widespread adoption of CSA practices needed to strengthen the climate resilience, productivity and food security of smallholder farming communities in Sub-Saharan Africa is daunting. Smallholder farms constitute approximately 80% of all farms in Sub-Saharan Africa and employ about 175 million people directly (Alliance for a Green Revolution in Africa, 2014). The Africa CSA Alliance has been advancing the implementation of the African Union Vision to reach 25 million farm households practicing CSA by 2025 (Vision 25 × 25), in line with the African Union's Comprehensive Africa Agriculture Development Programme (CAADP). Initiated in 2003 following the Maputo Declaration and strengthened by the Malabo Declaration in 2014, CAADP is a central pillar of Agenda 2063 (AU, 2025), promoting sustainable agricultural practices to enhance productivity and build environmental resilience. Agenda 2063 serves as Africa's strategic vision, guiding the continent toward inclusive development, unity, and collective prosperity. Through the Kampala Declaration, the African Union introduced a new agricultural strategy targeting a 45% increase in agrifood output by 2035 (AU, 2025), with an emphasis on transforming agri-food systems to achieve food security. This includes a 10-year CAADP Strategy and Action Plan (2026–2035), which sets out targets such as allocating 10% of national budges to agriculture and achieving 6% annual growth. CAADP also advocates for CSA techniques as a means to enhance climate resilience and advance sustainable agricultural systems across the continent. By scaling CSA initiatives within this framework, the Kampala Declaration and CAADP's emphasis on investment in agricultural research, infrastructure, and climate resilience can create an enabling environment for widespread adoption of CSA practices, thus accelerating the transition to more sustainable, climate-resilient farming systems across Africa.

However, despite the significant potential of CSA, efforts to scale CSA face persistent barriers that vary across different African countries. As noted by Barasa et al. (2021), a key challenge is the lack of national Climate-Smart Agriculture Investment Plans (CSAIPs) in some African countries. CSAIPs are national or regional strategies that identify and prioritize investments to scale up climate-smart agriculture (Jalango et al., 2022). A number of countries (e.g., Kenya, Zambia, and Uganda) are developing and adopting CSAIPs them to guide sustainable agricultural transformation and resilience building. Partey et al. (2018) identified poor financing, a lack of enabling policies, and limited understanding of CSA as additional barriers. As scaling of CSA practices is typically done using a CSA portfolio approach (where a bundle of CSA practices appropriate to a particular farming system or local context are scaled) country- or context-specific barriers to adoption of CSA practices can arise. While some barriers may be general to all smallholders, other barriers are context-specific or CSA practice-specific. For example, barriers to the adoption of CSA practices that smallholder farmers may face, include: the risk of reduced yields, increased resource demands (time, labor, money, land, rural energy etc.), lack of access to inputs, and lack of knowledge on how to shift to some CSA practices. Such barriers can be compounded by a lack of access to extension advisory services, whether provided in person or digitally.

For the level of CSA scaling required for impact on climate change adaptation and resilience within the necessary timeframes (i.e., within decades), digital delivery systems for CSA practices can be important for accelerating CSA scaling. However, with only 13% of smallholder farmers across Africa having accessed digital solutions, the digital divide between richer and poorer farmers remains a major challenge, particularly for the Sub-Saharan African region (Kudama et al., 2021).

Digital communication technologies as tools for scaling climate smart agriculture?

There are a wide range of digital tools and technologies that can be considered for their potential to enable the scaling of climate smart agriculture technologies and practices (Table 1). These include the provision of digital CSA agronomy advisory via the internet, web portals, mobile phone applications, SMS texts, interactive voice response (IVR), videos, and social media applications (Ingram and Maye, 2020). There is also potential for dual or multi-use platforms, where digital agronomy advisory supports can be communicated along with other supports (e.g., educational, health etc.). Indeed, the use of mobile phones has positive impacts not only on social interactions but also can be a powerful tool for enhancing agricultural productivity (Haruna et al., 2013). Amongst digital communication technologies, it should not be forgotten that both radio and television (TV) are two powerful tools with significant potential for supporting CSA scaling, where access will be more widespread for rural smallholder communities in Sub-Saharan Africa (when compared to internet or mobile phone based advisory).

A study in Tanzania has suggested that increased numbers of Internet users, and reduced cost of owning mobile phones and other digital devices will be necessary for large-scale dissemination of farming information (Kurgat et al., 2020). Some lessons can be learned from approaches to scaling of digital agronomy services in other regions. For instance, through internet and text messages the Rice Crop Manager (RCM) application ultimately benefited 20,000 Indian farmers through the training of 2,800 extension staff in Odisha District to better manage crop production (Sharma et al., 2020). Through such a training of trainers (ToT) approach using digital agronomy tools, extension workers obtained guidance on how to use the RCM application to perform farmer interviews and deliver advisories in a simplified short version of a single printed page. In the RCM initiative text messages and voice calls were sent to farmers as mechanisms of delivery of agronomy advisory services.

In the following section, we consider a broad range of digital technologies (e.g., radio, mobile phone apps, video, mobile phone apps, animations, and social media platforms) that can be harnessed for scaling CSA amongst smallholder farmers.

Radio as a communication channel to smallholder farmers

Radio has significant potential to reach many smallholder farmers in SSA (FRI, 2014). Indeed, is a standard medium of communication in the region that reaches multiple listeners, including rural communities, the private sector, religious organizations and the general public (Hansen et al., 2011; Beshir et al., 2015; Uzuegbu, 2016). In rural locations where TV access is not widespread, radio can be considered as the key channel for communication with smallholder farmers (Hudson et al., 2017). It is estimated that there are circa 800 million radios in SSA (Hudson et al., 2017; Ntshangase, 2021). From a localization perspective, more than 2000 different radio stations operate across ∼50 languages in SSA (Ntshangase, 2021).

Farm Radio International (FRI) uses radio to disseminate farming information and advisory across rural communities. In particular, FRI provides supports to African farmers through training (including opportunities to engage in radio programs) and broadcasting-based delivery of agricultural information. In

TABLE 1 Strengths and weaknesses of different channels for digital dissemination of agronomy and farmer training supports (organized from widest access to lowest access for rural smallholders).

Strength	Weakness	References
Radio		
Largely universal access (including for smallholders) Can reach a large population of listeners High quality content can be curated (e.g., by extension system)	Requires radio content generation and dissemination technology Radio on demand (i.e., playback) may not be accessible to all May be more popular amongst some age cohorts The timing of broadcasts may not suit some target audiences	Lwoga, 2010; Hudson et al., 2017; Ntshangase, 2021
Mobile phone applications		
SMS text messaging, IVR and voice over internet technology can be used to interact with farmers	The level and cost of phone technology dictates what level of communication applications farmers can use. Phone and internet skill and literacy levels can affect usefulness for some end-users	Kamel Ashour, 2012; Haruna et al., 2013; Baumüller, 2017; Ashraf et al., 2018; Evans, 2018; Kabbiri et al., 2018; Maredia et al., 2018; Omulo and Kumeh, 2020
Social media		
Existing channels can easily be used (especially by young farmers) Important for marketing of produce Widely used networking tools Reduce social isolation	Lack of access in smallholder rural areas Incorrect or misleading information can be disseminated—curation problem May not reach audiences intended i.e., income, urban and youth bias	Afande et al., 2015; Lohento and Ajilore, 2015; Latif et al., 2020
Videos		
Easy to capture the reality of the practice, context and situation	Can distort or misrepresent lived reality (e.g., romanticize drudgery tasks)	Bello-Bravo et al., 2018; Davis et al., 2018; Tetteh Kwasi Nuer et al., 2018; Tamene and Ashenafi, 2022
Video production has become easier (some farmers run their own social channels)	Digital divide due to income and infrastructure for many smallholders limits access	Subashini and Fernando, 2017; Sutherland and Marchand, 2021
Free (& open source) software and apps have simplified video production	High-quality video production (light, sound, content) is a specialist skill.	Simelane et al., 2019; Sousa et al., 2019
The cost of video and editing technology and software is dropping	High-end video production technology and editing out of reach of smallholder communities	Rohila et al., 2017; Silver and Johnson, 2018; Abate et al., 2019; Sharma et al., 2020
Locally produced video content can be disseminated to thousands or millions of farmers	How useful are generic videos? How many local-context videos are needed for effective CSA scaling? Who pays?	Singh et al., 2020; Tamene and Ashenafi, 2022
Animation-based videos have the potential to be used across multiple languages.	Animations require technical know-how and devices hence expensive to implement.	Singh et al., 2020; Tamene and Ashenafi, 2022

some instances, radio is being accessed through mobile phones as well as traditional radio technology (Gilberds and Myers, 2012). FRI (2014) has indicated that many smallholder farmers depend on radio as a key information source due to its widespread accessibility, convenience, affordability, fast interaction, and ability to be accessed in local languages, which is a critical factor for many farming communities. Farmers can benefit from radio programs that share information on both traditional and innovative farming methods. In Ghana, household welfare improved following agricultural radio broadcasts by women cocoa farmers, where radio was found to be more effective than other alternatives in this context (Awuah-Frimpong et al., 2024).

Rural women in Ethiopia and Tanzania supported by the Farm Radio project improved their agricultural practices through mobile phone recordings (Hudson et al., 2017). In the project, the recorded voices contributed content to radio programs for their peers. The training of trainers approach had a significant multiplication effect—while only 13 local radio broadcasters were trained, 8 million listeners were reached. The stories of rural women farmers were incorporated into the radio broadcasting. A similar study in the Northern and Southern highlands of Tanzania observed an uptake of legume-based sustainable agricultural intensification practices and technologies as a result of communication campaigns using radio and/or short SMS messages on mobile phones (Silvestri et al., 2021). While the study found that awareness and adoption of the legume technologies increased where SMS supported the radio campaign, radio alone was the most cost-effective (2.1 farmers adopting at least 1 new legume practice per US$) when compared to SMS alone (0.5 farmers adopting per US$) or radio and SMS combined (0.4 farmers adopting per US$) (Silvestri et al., 2021).

Mobile phone apps as communication channels to smallholder farmers

Mobile phone technology can improve information access for farmers by reducing the cost of accessing agriculture-related information and enabling access to markets (Simelane et al., 2019). Mobile phone applications can enhance agricultural productivity and improve rural food security through improving access to information for farmers (Mdoda et al., 2024). While many farmers may have access to a mobile phone, the level of technology of the phone may differ dramatically. For instance, while in some areas (e.g., rural Pongola, KwaZulu-Natal, South Africa) it was found based on small sample sizes ($n = 93$ farmers), that the vast majority (94.6%) of farmers had mobile phones, the type of phone spanned basic to smartphones (Simelane et al., 2019). Nonetheless, mobile phones can provide a range of useful services to farmers. For instance, apart from making calls and calculations, the majority of farmers in the North Senatorial Zone of Kaduna State in Nigeria were found to use mobile phones for sourcing information about agri-extension advisory (Haruna et al., 2013). While universal access by smallholders to quality agri-advisory services is ideal, the reality is that many smallholder farmers face access barriers such as the high cost of subscription, electricity access for charging, and poor quality mobile phones. Indeed, farmers in Kafr El-Wak Village, El-Behaira Governorate in Egypt who used mobile phones to access extension services highlighted challenges such as high costs of calls and lack of experience of using mobile phones for agri-advisory supports (Kamel Ashour, 2012).

Interactive voice response (IVR) systems allow users to interact with a computer-operated telephone system via voice (speech) and/or keypad commands. An emerging means of delivering advisory and training to farmers via mobile phones is through Interactive Voice Response (IVR) systems, which are more recently augmented by Generative AI (GenAI). These systems can deliver immediate tailored information by calling a designated number, scaling the service to include users without app-enabled devices. The use of natural language processing and GenAI for interpreting spoken queries in local dialects and for the dissemination of context-specific advisory, can reduce the cost compared to face-to-face (f2f) extension services, possibly reducing the financial “barrier to entry” faced by smallholder farmers. In principle, IVR technology can facilitate accessible, time-efficient and flexible training in the local language of the user and has potential to support those with limited literacy and digital skills (Dione et al., 2021). Platforms engaging with smallholder farmers, such as Viamo and Digital Green, have begun implementing and scaling such systems. It is argued that such services have the potential to address gender inclusivity in accessing advisory services and information, as female farmers often face more constraints in attending in-person trainings. For instance, according to the Ask Viamo Anything pilot report the average user was female, aged 18–24 and showed higher engagement in the platform, particularly in relation to the sustainable development goals (SDGs) (Deshpande et al., 2025).

Video delivery for training of smallholder farmers

In principle, there is a “democratization” potential to make high-quality and locally relevant training videos available to all farmers across the agricultural sector. Indeed, video training is considered one of the most promising approaches to address the information dissemination challenges experienced when engaging with youth, women, poor and marginalized groups (Davis et al., 2018; Alföldi et al., 2019). Videos can be used to raise awareness, improve skills and facilitate peer-to-peer training, while encouraging creativity across multiple video creators. Localization is a key issue for effective extension training content and methodologies, in particular where CSA training materials will need to be communicated through local languages. The “last mile” digital delivery of extension training can be a challenge in Sub-Saharan Africa, which has a complex linguistic landscape. In the region, indigenous local languages with only thousands of speakers co-exist alongside national and regional trade languages (Gershman and Rivera, 2018).

In Ethiopia farmers have been supported by extension services to generate locally-produced videos that can be disseminated using battery-powered projectors. The use of local languages in such videos enabled each villager to better understand and participate in the training. Robust battery powered projectors were essential to overcome the barriers of electricity and internet coverage. The lack of access to electricity, internet and bandwidth across smallholder communities is a major barrier to scaling of video-based training. Only half of the population of Sub-Saharan Africa has access to electricity, with lower levels of access in rural areas compared to urban. The GSM Association (GSMA)—which is a trade body representing mobile network operators—indicates that while mobile phone access is increasing, there is greater access to 3G rather than 4G connections. However, in 2020 the GSMA estimated that half the population in Sub-Saharan Africa had access to a 4G network.

A key challenge is how to facilitate farmers (especially smallholder farming communities) to generate and curate videos with useful, relevant and high-quality content (Uzuegbu, 2016). In addition to the video quality and relevance challenge, the additional challenge is how to disseminate such videos across thousands (indeed millions) of smallholder farmers (Uzuegbu, 2016). However, approaches are emerging for farmer-generated content and dissemination, where there can be learning opportunities across regions. For instance, Van Campenhout et al. (2017) highlighted how participatory videos in India enhanced interaction between the community and researchers during screening discussions. Volunteers were trained on how to shoot and edit videos using simple editing techniques. The video event raised the confidence of both male and female farmers, as well as the video volunteers, while the farmers were proud of being part of the video. Similar approaches have been conducted in Ethiopia, where farmers were supported to make videos for peer-to-peer learning (Abate et al., 2019). Van Mele (2011a) has indicated how the Grameen organization adopted rice videos produced in Asia and used them in Uganda to help farmers to implement more sustainable rice cultivation.

Useful repositories of publicly available, open-access farmer training videos are available online from providers such as Digital Green and Access Agriculture. However, not every farmer is in a position to use them due to internet access challenges, the absence of digital devices and the high cost of internet bundles for downloading or real-time playing (Abate et al., 2019). Nonetheless, with sufficient resources and support, videos can be downloaded for replaying to farmers using local projectors. For, instance in Southern India, small-scale farmers, extension staff and Oxfam worked together to generate video-based training on farm tasks such as application of manure, fertilizer and pesticides and on drip irrigation (Joras et al., 2020). With the support of Digital Green, farmers and the local extension agents produced, edited, and disseminated videos using a pico projector that was supplied by Digital Green (Joras et al., 2020).

The potential of a particular mode of delivery typically depends on popularity, accessibility, cost, and ease of use (Tadesse and Bahiigwa, 2015; Kudama et al., 2021). As mobile phone technology evolves, new opportunities for peer-to-peer information, file and video sharing are emerging. If designed as a short-duration (small file size), both videos and animations can be transmitted on mobile phones from farmer to farmer through Bluetooth technology (Bello-Bravo et al., 2018; Maredia et al., 2018). In principle, the audiovisual nature of videos and animations make it suitable for diverse population groups as compared to written materials, potentially circumventing some of the challenges of illiteracy. Table 2 indicates a range of organizations engaged in video-based training for farmers in developing countries.

Digital Green's approach to digital agronomy support for smallholders

Digital Green provides an example of how targeted agricultural information can be effectively disseminated to smallholder farmers using videos. Digital Green employs video as a communication tool that can be integrated into existing extension networks to enhance their effectiveness. Rather than creating video content on their own, Digital Green works with established groups who use a group discussion format to provide more instructions following questions that may arise after watching videos (Gandhi et al., 2009). By 2019, Digital Green indicated that it had reached 7,448 villages and over 640,000 community members in Ethiopia, Ghana, India and Tanzania with agricultural innovation through video training (Bentley et al., 2015, 2019).

Digital Green provides useful insights into important considerations when using digital technologies to share information on CSA practices and technologies. Digital Green features local farmers in their videos, based on their findings that farmers are more likely to use practices that are already in use by other farmers in their locality. Another consideration when generating videos, is to make videos according to local village demand, including the type of practice, language and cultural aspect of the area. For research and agricultural extension groups with interest in the use of participatory video as a way to engage smallholder farmers with new tools and techniques for climate-smart agriculture, Digital Green provides useful examples, experience and insights into how this can be done.

A similar initiative to Digital Green was carried out in Kamwenge district, Uganda. A video-mediated extension approach (VMEA) was assessed as a means to enhance rice farmers' access to information, and their desire to engage with new innovations in farming. The study, which involved 100 farmers, revealed that VMEA had a positive influence on farmers' awareness, knowledge, and likelihood to share knowledge related to rice production, including, planting in lines, timely weed control, seed selection and use of tarpaulins for drying rice. The VMEA initiative observed that extension staff needed to be present to provide additional support for social learning, and are still needed to support farmers in recording videos about their accomplished experiments to share with other farmers (Karubanga et al., 2017). Both initiatives demonstrate the potential of video as a digital tool to enhance and amplify the essential work done by extension workers.

Figure 2 indicates the five steps used by Digital Green to implement successful participatory videos. Through the process, communities participate in the activity without technical experts. One challenge can be the absence of digital devices and connectivity.

Table 3 indicates the a range of popular farmer training videos on YouTube by Digital Green (top 10 highest viewers). The channel has over 345,000 subscribers. The table shows that the video titled Garlic Solution Hindi Muzaffarpur had the highest views (4,620,717) on the channel compared to other videos. While it is not clear whether video views, likes and comments translate into practical use of the training video for training of farmers, this data reveals some level of engagement with the videos, which may indicate that farmers (or others with an interest in farmer training with videos) are interested in receiving agricultural information in video formats.

TABLE 2 Some examples of organizations involved in video-based training of farmers across a range of developing countries (including training modalities employed).

Organization	Training modality	Countries & regions
Digital Green	Mobile Phone, Pico Projector (Videos)	India, Ethiopia, Kenya, Malawi, Nepal, Nigeria, Bangladesh
Access Agriculture	Videos through MP3 or MP4 formats, and Solar power projectors	Africa, Asia, Latin America
Mkulima Young	Social media platforms	Kenya, Rwanda, Zambia, Malawi, Zimbabwe, Benin, Ghana. Burundi, Namibia, Botswana, Ethiopia, South Sudan, Mozambique
Farm Africa	Radio, Mobile Phones	Kenya, Tanzania, Ethiopia, Uganda, DR Congo
Farm Radio	Radio	East, West Africa and Southern Africa
Sasakawa Africa Association	Mobile, Radio, WhatsApp, videos, projectors	Uganda, Ethiopia, Nigeria, Mali

Access agriculture's approach to digital agronomy support for smallholders

Another organization that supports farmers to video-document their agricultural practices is Access Agriculture, which produces training videos for smallholder farmers, including on organic farming and agroecology. Around 90 million farmers have received training through farmer-to-farmer video trainings facilitated by Access Agriculture. The approach allows young rural entrepreneurs to generate income from showing and selling the videos. Access Agriculture uses EcoAgTube, a video-sharing platform for anyone with an interest in ecological farming and food processing, to share experiences and showcase local innovations through videos using local and global languages. The videos uploaded are

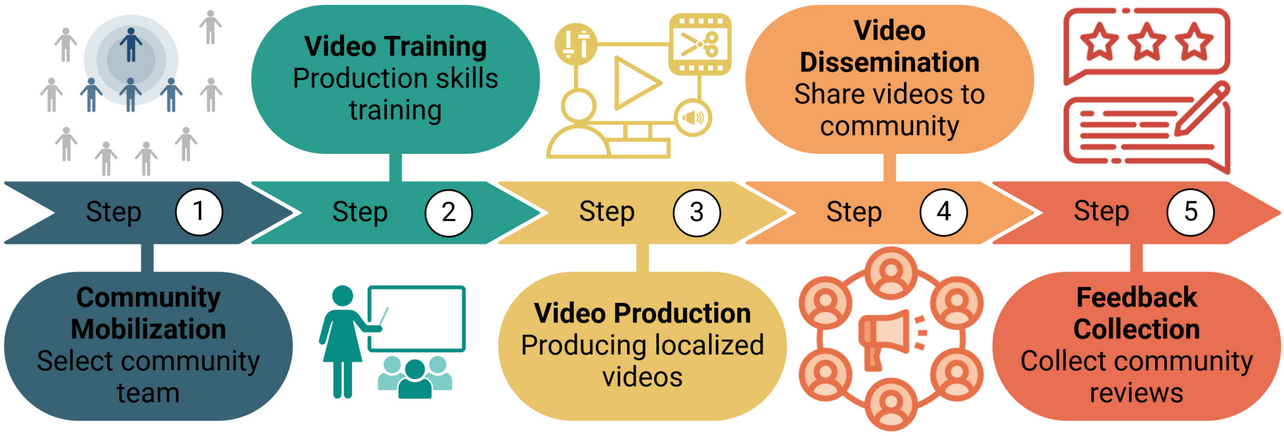

FIGURE 2
Flowchart of fundamental steps in the participatory video production process adapted from Digital Green initiative. Source: Digital Green.

TABLE 3 Popular videos on Digital Green's YouTube channel (as of April 2025)*.

Farmer training video	Language	Year	Views	Likes	Comments
Garlic Solution Hindi Muzaffarpur	Bhojpuri	2016	4,620,717	2,200	212
Conoweeder JSLPS Dig Green	Bhojpuri	2016	3,737,724	2,700	82
Chilly transplantation Muzaffarpur	Bhojpuri	2015	3,027,989	1,300	149
Micro Planning Purnia	Hindi, Bhojpuri	2015	2,719,974	3,300	84
Coconut planting method_Tiptur	Kannada	2014	2,459,024	16,000	356
Oyster Mushroom inJeevika Bihar	Hindi	2014	2,242,820	12,000	509
Magic Compost DG Sadri Jharkhand	Bhojpuri		1,780,642	1,400	143
Jeevamruth (liquid manure) Kannada BAIF Karnataka	Kannada	2011	1,391,423	11,000	278

*Data in this table was extracted from Digital Green's YouTube channel (April 2025), https://www.youtube.com/@digitalgreenorg.

curated across categories such as Agriculture, Capacity building, Climate and environment, Ecotourism, Food and health, Forestry, Green building and energy, Inspiring action, Land and water, Livestock poultry aquaculture and Beekeeping. Upon request, Access Agriculture encourages a diverse array of users including youth, elders, men and women to upload their own videos in any language and encourages digital training peers to do so as well. Access Agriculture hosted videos on their website reaching at least 897,000 farmers, used by several organizations in 80 countries.

To ensure quality in bottom-up video-based training, initiatives for curating and quality control can be considered. For instance, with Access Agriculture through the EcoAgTube channel, farmers or anyone else can share videos on the channel which will be assessed by experts before approval and publishing (Alföldi et al., 2019). There are guidelines that enable digitally-inexperienced farmers to produce videos for knowledge dissemination and enhanced learning. Monitoring and evaluation is vital to assure of the quality of videos available online but also to avoid any misconceptions that could arise.

While digital tools and content can be used to distribute information to and between farmers, they there are access challenges such as to electricity, phone networks and the internet (Gandhi et al., 2009; Van Mele, 2011b; Afroz et al., 2014; Owiti et al., 2023). To overcome this challenge, Access Agriculture uses a portable solar-powered projector to screen videos offline to educate farmers in their local languages (Ryoya and Steensland, 2021). The projector system consists of a projector, projection screen, rechargeable speaker, and a Universal Serial Bus (USB) stick with videos. Access Agriculture works with young entrepreneurs who share the videos in rural areas for a low cost, as well as selling DVDs with copies of videos (Chowdhury et al., 2012). Similarly, Digital Green uses a pico station projector with rechargeable batteries to disseminate agricultural information among farmers (Abate et al., 2019). With portable projectors with off-grid energy sources that can be moved from rural community to community by bicycle or motorbike, the challenges of lack of access to electricity, phone networks and internet can be overcome.

The range of popular farmer training videos on the Access Agriculture's YouTube channel (which has over 73,600 subscribers) in Table 4 suggests that different videos have different adoption rates. Some have more audience and responses, possibly because of the type of practice advertised, language used, or users' interest in the channel.

TABLE 4 Popular videos on Access Agriculture's YouTube channel (as of April 2025)*.

Farmer training video	Language	Year	Views	Likes	Comments
Methodes naturelles pour garder les poulets en bonne santé	French	2021	351,222	3,400	52
Hacer concentrado de bajo costo	Spanish	2020	280,142	1,100	30
The onion nursery	English	2019	212,715	1,200	24
Desparasitar a chivos y ovejas con remedios de plantas	Spanish	2019	199,504	979	38
Maintenir les moutons en bonne santé	French	2019	174,104	665	18
Harvesting and storing soya bean seed	English	2019	168,164	735	35
Goutte à goutte pour tomates	French	2018	167,132	762	42
Managing onion diseases	English	2019	127,844	578	45

*Data in this table was extracted from Access Agriculture's YouTube channel (April 2025), https://www.youtube.com/@AccessAgriculture.

Using animation for digital agronomy support for smallholders

Animation is a video-making technique, where still images or drawings are digitally manipulated to move in space and time. Organizations involved in digital agriculture have used animations when generating farming training because animated visuals in local languages can improve viewer's learning gains compared to more traditional learning extension methods (Bello-Bravo et al., 2018). One example of an initiative using animations to disseminate scientific information in local languages is Scientific Animations Without Borders (SAWBO). SAWBO creates and works with local groups to deploy educational videos in local languages and facilitate access to information sharing to individuals in the developing world (Bello-Bravo et al., 2018).

SAWBO is an initiative by Illinois Urbana-Champaign University (Rodriguez-Domenech et al., 2019) for the production of open-access, publicly-available and downloadable animated educational materials for farmers in local languages. The animations are available in a variety of file formats including mp4, MOV, 3gp, and 3gp lite and can be accessed via cell phones, smartphones, computers and broadcast technologies. SAWBO animations address a number of SDGs including: no poverty, zero hunger, quality education, reduced inequality, responsible consumption and production, and life on land.

The SAWBO animations aim to provide education about specific diseases, value chain and agricultural challenges, and techniques (Bello-Bravo et al., 2018). They are created using culturally acceptable visual images and translated into local languages. The videos can be downloaded freely. Using SAWBO's Deployer App on Android phones, they can be viewed when the device has no access to the Internet (Bello-Bravo et al., 2018) and can be transferred to other cell phones using Bluetooth and shared with farmers, extension agents and other stakeholders (Bello-Bravo et al., 2018).

One study conducted in Burkina Faso tested the effectiveness of animated educational videos in enhancing cowpea post-harvest with two techniques (drying using solar disinfected and storing in triple bags technologies). The animations were created by researchers as instructional videos, to expose users to concepts and disseminate the knowledge to as many farmers as possible. The study revealed that mobile phone-based animated videos have the potential to induce learning among low-literacy farmers (Maredia et al., 2018). The study involved 48 villages across two provinces in which participants were randomly assigned to receive the training through two methods: watching a live demonstration or watching animated videos on their mobile phones. The results indicated that the group that used animations had a better understanding of the triple bag (8%) and solar disinfestations (16%) technology described in the video and live demonstration, than those farmers who were taught using only live demonstration (Maredia et al., 2018).

Popular farmer training animations, highlighted in Table 5 on YouTube by SAWBO, are made in international and local languages. Some of the videos have more likes, comments and views than others. However, it is not known whether the videos with higher statistics have a higher impact or are the most successful. The SAWBO YouTube channel has over 54,000 subscribers.

Digital agronomy mobile phone applications for delivery of agri-extension training

Enabling smallholder farmers to develop, disseminate, and benefit (including, profit) from digitally-delivered agri-extension training (including farmer-generated videos) can be considered a form of democratization of agri-extension training. Furthermore, such a peer-to-peer approach could be used to reverse or rebalance power relations between smallholder farmers and external experts (e.g., extension agents, private sector suppliers, scientists) and foster bottom-up development and dissemination of more effective CSA practices (Chambers et al., 1989; Chambers, 1997; Thro and Spillane, 2003; Chambers, 2014).

Several studies have investigated the use of video training and the involvement of farmers in the video process (Gandhi et al., 2009; Van Mele, 2011b; Alföldi et al., 2019). However, due to farmer's limited knowledge and the opportunity cost of their time, they only participated in the filming while editing. Final deployment was invariably done by experts, including extension agents (Gandhi et al., 2009; Van Mele, 2011b; Alföldi et al., 2019). Benefits of video training have been reported for women groups in Benin that produced and sold parboiled rice (Zossou et al., 2010).

TABLE 5 Popular animation videos on YouTube by SAWBO YouTube channel (as of April 2025)*.

Farmer training video	Language	Year	Views	Likes	Comments
Survival Farming: Drip Irrigation	Spanish	2014	2,031,913	17,000	183
Postharvest Loss: Jerrycan Bean Storage	English	2021	1,658,332	34	5
Importance of Adopting New Lentil Varieties	English	2023	592,914	1	0
How to Identify and Scout for Fall Armyworm	Bengali	2018	446,982	265	17
Properly Storing Dried Grains and Legumes Using Hermetically Sealed Bags	English	2021	373,701	255	33
Nayām prajātikā dalahana bāliharu lagā'unuko mahatva	Nepali	2023	346.771	1	0
Pertes après récolte: Stockage des haricots Jerrycan	French	2024	252,637	34	4
Using Native Shrubs to Increase Healthy and Crop Yield	Wolof	2022	118,856	30	4

*Data in this table was extracted from SAWBO's YouTube channel (April 2025), https://www.youtube.com/@SAWBOsm.

There are many digital agronomy mobile applications developed and also many under development. An example of a mobile application which provides advisory training support on agricultural practices is the ECHOcommunity, available on Android and iPhone. Indian dairy farmers use the e-Gopala application which provides advisory services on animal nutrition, veterinary and livestock trading. Farmers are informed about various government schemes via multilingual services. Through the iCow platform, farmers can optimize their production systems, and access service providers who send feedback and share successes. The Kurima Mari App assists farmers in getting information about crops and livestock by utilizing expert contacts to increase productivity in farming and access to markets. The Practical Answers app is a mobile application that allows users to employ a range of innovative knowledge in agriculture, and other natural-based resources. The WOCAT-SLM app provides farmer-oriented support on Sustainable Land Management (SLM) including how land users can maintain natural resources such as soils, water, and vegetation. The E-Price App, a mobile internet application, has helped address price volatility among rural farmers and agri-businesses in rural China through the provision of price information services from production, logistics, retail, agricultural materials, and price analysis (Zhang et al., 2016).

Hello Tractor is a digital market interface that facilitates interactions and transactions among farmers and smart tractor owners in Nigeria, Kenya, Mozambique and Asian countries to buy or rent smart tractors for farming purposes (Hinson et al., 2019). Other online technologies include wefarm, initiated in 2015 in Kenya, which helps farmer-to-farmer communication without a need for internet connectivity (Omulo and Kumeh, 2020). Through the platform farmers can register, ask agricultural-related questions and receive responses via Short Message Service (SMS) and online chat services. Through wefarm, a voluntary social enterprise, farmers are connected to other farmers where they can collaborate on a variety of agricultural challenges. The wefarm platform is successful with over 1.8 million farmers registered in Kenya, Uganda and Tanzania, engaged in over 4 million questions posed gaining 9.6 million responses (Omulo and Kumeh, 2020). These mobile applications and platforms provide some examples of the diversity of digital agronomy mobile applications in existence and under development.

There are a plethora of digital agronomy platforms and apps under development, globally and across Africa, many of which aim to support smallholder farmers. Examples include CIMMYT's AgroTutor which has been developed as a digital public good for advisory service providers as well as a decision-support solution for smallholder farmers. iSDA's Virtual Agronomist, launched in 2024 by Rothamsted Research, the World Agroforestry Center (ICRAF) and the International Institute of Tropical Agriculture (IITA), has provided agronomic advisories for over 200,000 smallholder plots across seven countries and over 17 crops in Africa. The Lersha platform in Ethiopia provides digital agronomy supports to over 270,000 farmers, involving over 2,000 Lersha agents. The GIZ-funded Agriculture Information Exchange Platform aims to empower smallholder farmers through inclusive AI solutions for agricultural advisory services, where four minimal viable products (DynAg, Digital Green, Viamo & partners, Tech for Her) are being tested with farmers in Bihar and India focused on farmer needs (e.g., crop planting, climate issues and value chains).

From an efficiency and sustainable business model perspective, it can be questioned whether having multiple (possibly competing) digital agronomy mobile applications is the most cost-effective way to deliver digital CSA supports to millions of farmers, especially "last mile" smallholders. However, standardization and over-centralization of digital agronomy mobile applications and platforms may also stifle innovation. Nonetheless, there is a need and opportunity for some standardization and quality control of digital agronomy services to ensure that smallholders are not provided with erroneous or misleading agronomy supports.

Using existing social media platforms to enable scaling of good agronomy and CSA practices?

Social media is a powerful tool for distributing information, especially among young farmers and next-generation farmers. Amongst its greatest strengths are its growing pervasiveness (reach) and its interactivity, following a bottom-up rather than a top-down approach (Saravanan et al., 2015). With the increased spread of digital technologies, particularly Internet and mobile phone subscriptions (Van Campenhout et al., 2017; Evans, 2018) among rural Africans (in particular, youth), social media is helping more farmers gain access to necessary information. Social media platforms can attract a large user base thanks to services like hosting pages, groups, and accounts, which allow for multimedia content to be shared freely (Saravanan et al., 2015).

The world's internet users increasingly depend on search engines such as Google, Yahoo, Bing and DucKDuckGo, along with a range of social media platforms (Facebook/Meta, YouTube, WhatsApp, Twitter/X, Instagram, YouTube, TikTok, WeChat, Telegram etc) to interact with others and search for or access information and video content. Datareportal indicates that there are 5.2 billion users of social media platforms globally (Datareportal, 2025). As of February 2025, the number of users of many of the leading social media platforms is in the order of billions e.g., Facebook/Meta (3 billion monthly active users), YouTube (2.5 billion per month), WhatsApp (2 billion per month), TikTok (1.6 billion), WeChat (1.4 billion) (Datareportal, 2025). Despite the privacy and data control issues associated with most social media platforms, social media platforms have major potential to support farmers when harnessed or adapted for more effective scaling. In addition to their user-friendly interfaces, a key strength of such social media platforms is their end-user reach both nationally and globally.

Although not specifically focused on agriculture, there are some compelling advantages to the use of existing social media platforms for supporting digital agronomy and CSA scaling, particularly where the platform allows for user-created and user-curated content to be developed and shared. In addition, existing social media platforms can allow "communities of practice" and "self-help" groups to emerge which can allow peer to peer dissemination of agronomy and CSA knowledge, practices and technologies. For instance, a youth group in Kenya uses the Mkulima Young Champions Facebook account to provide farming updates and discuss agricultural topics, successes and challenges with their follower base (Lohento and Ajilore, 2015). Indeed, during the COVID-19 pandemic, farmers in China used the TikTok platform to provide accessibility to agricultural producers to promote and sell crops in live broadcasting (Zhu, 2020). The Greenthumb Community Based Organization (CBO), a youth group in Kenya, uses Facebook to conduct online discussions about fish production. Where youth become more engaged in fish farming through the availability of information, markets and solutions.

Using digital communication technologies to facilitate peer-to-peer training in smallholder farming communities

Agricultural extension services remain critical for bridging the gap between agricultural research findings and on-farm adoption of knowledge and technologies (Rickards et al., 2025). CSA adoption depends on farmers engaging with information presented in a way that feels actionable and relevant, particularly evidence of yield and profit outcomes (Lasdun et al., 2023). Farmer-to-farmer extension campaigns that utilize existing social networks to incentivize and mobilize farmers remains an effective strategy (Lasdun et al., 2023; Nyambo et al., 2022; Rickards et al., 2025).

Digital tools offer transformative potential through scalability, real-time interaction with peers and tailored content delivery, but their impact on peer-to-peer learning and extension services is constrained by low digital literacy rates, poor interface usability, lack of farmer centric design and uneven internet access (Rickards et al., 2025). Nonetheless, digital agronomy approaches can be used to enable peer-to-peer (i.e., farmer to farmer) training where there is a clear incentive for farmers to train their peers. For instance, through the services from organizations such as Access Agriculture farmers can use smartphones and computers to watch farmer training videos, either alone or in groups (Bentley et al., 2019). To reduce data consumption (for example from streaming) it is possible to download videos on USB or DVDs for later viewing or dissemination. There is an increasing adoption of cell phones across Africa (Sousa et al., 2019). However, due to cost, the transition to individually-owned smartphones amongst smallholders is slow.

While many smallholders may own or have access to a mobile phone (Alper and Miktus, 2019), only a small fraction in most African countries own or have access to a smartphone. Even where phones with improved functionality are available (including smartphones) there can be challenges such as digital literacy that can limit some end-users from using all of the features of the phone that could potentially be of use to them. In Mali and Burkina Faso, it was found that some farmers watched entertainment videos on their phones, while the same platform could be used to search for agricultural information (Maredia et al., 2018). Video entertainment and music are a potential source of income for youth, particularly through broadcasting videos to elders and illiterate with no access to technology (Van Campenhout et al., 2017). However, when many knowledgeable youths migrate to urban areas for job opportunities it can reduce the digital know-how in rural areas. Lack of skills in good practices when using of the internet and social media for agribusiness can hinder them from participating in agribusiness.

In particular, peer-to-peer training using mobile education platforms can be an effective tool for improving farmers' agricultural practices (Patii et al., 2018). The use of training videos featuring local members of rural communities can help to attract more farmers interest (Joras et al., 2020). Providing videos to farmers on memory cards for later use at their preferred time on phones or other electronic devices is a useful option, providing freedom for farmers to engage with learning materials at a time and place that is convenient for them (Joras et al., 2020).

Digital agronomy to augment rather than replace extension workers and systems

Research studies in south-western Uganda and Muzaffargarh district in Pakistan have indicated that conventional ways of delivering information like personal visits, meetings and mass discussions are no longer as effective due to population growth, limited number of extension experts and limited resources in rural areas (Van Campenhout et al., 2017; Khan et al., 2019). To address such challenges, mobile digital technology can be an important tool to disseminate information about crop production and reducing poverty among smallholder farmers (Misaki et al., 2018). Studies indicate that there is extensive research underway on CSA, and also highlight the role of media channels such as radio and mobile phones in providing information to smallholder farmers (Juvvadi et al., 2013; Lipper et al., 2014; Rohila et al., 2017). Many of the ICT in agriculture technologies provide information about markets. Low-cost technologies like texts, voice messaging, and interactive voice response (IVR) systems can reduce or augment farmer's dependencies on extension officers and other experts as a means to access valuable information (Tadesse and Bahiigwa, 2015; Hudson et al., 2017).

Haruna et al. (2013) highlight that the use of mobile phones not only has positive impacts on social interactions, but is also a tool for enhancing farm productivity, as mobile phone technology can play a role on all stages of agricultural value chains from land preparation, farming, harvesting and post-harvest. With technology advancements and internet expansion in many countries (Van Campenhout et al., 2017) it is becoming more possible to use training videos to deliver information to farmers. In countries where videos have been produced, extension experts have been at the forefront of facilitating the digitalization process using local language, and by using battery projectors to overcome electricity and internet challenges (Gandhi et al., 2009).

Perceptions that mobile phone-based agronomy or mobile phone-based CSA service could replace completely human extension agents seem misfounded or exaggerated. The reality is that digital agronomy services will most likely be used to augment and improve the quality of delivery of extension services by human extension agencies. Digital platforms can enhance the way agricultural knowledge can be produced, utilized and communicated among farmers, thus enabling informed decisions for farming (Ingram and Maye, 2020). Farmers in Kenya adopted text messages and video approaches through the iCow initiative, a centralized cattle management system associated with improved milk production, and also farm and household income among smallholder dairy farmers (Marwa et al., 2020).

In the emerging world of AI chatbots and AI-assisted decision-making, there are strong recommendations for maintaining "humans in the loop" as such approaches become more powerful over time (Drori and Te'eni, 2024). Yet the mobile phone has the potential to act as a communication medium to augment face-to-face interactions between extension agents and the rural communities they serve. However, there can also be feelings of limited ownership that farmers encounter which can disincentivize their full participation in the technology (Sousa et al., 2019).

Digital technology is also influencing rural development and the SDG targets through remittances. Remittances from urban to rural areas are an increasingly important source of investment in agriculture and innovation (Schraven, 2016; Sulemana et al., 2019). Remittances can be in monetary or non-monetary goods, received from either abroad or internally within the country. There is significant potential for remittances to support rural livelihoods (Williams, 2016). In Sub-Saharan Africa, the rate of remittances grew by 11.4% and reached $38 billion US dollars in 2017 before a slight slow in 2016 (Ebadi et al., 2020).

Many smallholder farmers depend on subsistence farming and sell most of the products as soon as they harvest for other basic needs. It is considered that most of their remittances cater for food rather than investing in agricultural production (Williams, 2016). A survey by Onyango et al. (2021) asserted that 82% of households in Southern Africa spend remittances on food, while only 24% invest remittances in agricultural activity. The same study reported that one-third of remittances are received in the form of goods such as food. Mobile phones with internet connectivity have been the focal digital platforms for transferring remittances within and between countries to rural populations in Sub-Saharan Africa (Silver and Johnson, 2018). Onyango et al. (2021) have indicated that Mpesa mobile money application enhanced cash dispatching to Kenya since 2007 and has influenced rural-urban connectivity.

The rise of machine learning and AI—What implications for digital agronomy supports for smallholders?

As in many domains, artificial intelligence (AI) is increasingly being recognized as a promising transformative tool for smallholder agriculture, potentially providing AI-enabled solutions and supports to improve productivity, sustainability, and resilience. For instance, AI-driven intelligent sensor networks have shown potential to increase yields through real-time climate monitoring and precision farming strategies tailored to smallholders contexts (Diyaol, 2025). Machine learning and deep learning technologies are now considered to be reshaping crop production, nothwithstanding the scalability challenges for smallholder farming systems with limited infrastructure (Ali et al., 2025). In Nigeria, AI is being applied to pest control, weeding, and livestock management to enhance food production and farmer livelihoods (Amuda and Alabdulrahman, 2024). First generation platforms such as Farmer.Chat already demonstrate the promise and viability of generative AI in reaching thousands of smallholders with personalized agricultural advice, potentially enabling the scalability of digital advisory services (Singh et al., 2020). Despite these advancements, barriers such as digital literacy and connectivity remain, particularly in Sub-Saharan Africa, where digitalization within smallholder farming systems and communities presents both challenges and opportunities (Choruma et al., 2024).

Complementing these developments, Machine Learning (ML) algorithms are seeing increased adoption for deriving insights from big data, particularly remote sensing data and projected climate models. This can reduce reliance on traditional field sampling methods to provide more comprehensive information at a greatly reduced cost. Using the predictive power of ML data-driven insights, farmers can be empowered to improve the resilience and efficacy of their farming practices (Mmbando, 2025). With better and tailored access to information on optimal planting time, risks of pests and disease, irrigation scheduling, fertilizer application and crop selection, smallholder farmers can be supported to enhance both resilience and yield (Elbehri and Chestnov, 2021). As machine learning technology becomes more integrated into the decision-making processes at farm and value chain levels, ensuring equitable access to the data and decision-making insights will likely be a requirement for the successful adoption of CSA practices in smallholder farmers.

An emerging and powerful implementation of ML and AI is the emergence of Digital Twins, such as the flagship Destination Earth (DestinE) initiative (Nativi and Craglia, 2020). DestinE consolidates Earth Observation (EO) data, multidecadal climate projections and a range of pretrained AI algorithms, to simulate our planet under different climate scenarios. Digital twin approaches have promise for tackling the fragmentation of localized datasets and algorithms, and can focus global technical capacity and resources into one unified accessible platform. By simulating our Earth system (and agricultural systems therein), there is significant opportunity to test climate adaptation strategies and anticipate agricultural system tipping points before they occur. There is significant opportunity for integration of Digital Twin approaches into decision-making and early warning systems from landscape to farm scales, to accelerate adoption of CSA practices and technologies.

Digital technologies and climate smart agriculture can contribute to achieving some of the sustainable development goal targets—Some considerations

A number of commentators have asserted the potential of digital transformations in achieving the Sustainable Development Goals (SDGs) (Castro et al., 2021; Gupta and Rhyner, 2022; Van Vuuren et al., 2022). The 2030 Agenda for Action which encompasses the SDGs adopted in 2015 by the United Nations General Assembly had a common goal of a sustainable future for everyone considering the aspects of economy, social inclusiveness, and environmental prosperity (Tsalis et al., 2020). Furthermore, in Agenda 2063 (Smidt and Jokonya, 2022) adopted by the African Union (AU), modernized agriculture is expected to increase productivity through a range of initiatives, including mechanization, irrigation expansion and improved agriculture value chains.

Each SDG has a set of SDG targets associated with it. For instance, SDG target 9.c consists of the need to achieve universal and affordable internet access by 2020 to help the agricultural sector achieve the goal of improved productivity (Montes et al., 2020). It is widely anticipated in national agricultural plans that in the future many smallholder farmers will transition to more commercial farming, in a manner that supports the achievement of SDGs related to eradicating poverty (SDG1) and reducing hunger (SDG2).

Examples of efforts to help achieve SDG targets via digital advisory include a project in East Africa (Tanzania, Kenya, and Uganda), where farmers can adapt better to climate stresses through improved practices presented via the Television show "Shamba Shape Up" (Loboguerrero et al., 2018). The Shamba Shape Up initiative substituted traditional approaches and provided on-farm interventions toward climate adaptation actions. The study reported that over 9 million people were reached by Shamba Shape Up in 2014, with 42% engaging in recommended practices because of the show. This reach informed development partners and other stakeholders to invest in the show making it also accessible on other applications such as mobile, short messages, and over the internet (Loboguerrero et al., 2018).

Balogun et al. (2020) have highlighted the power of digitalization in Mozambique where the National Institute of Meteorology (INAM) improved the technical capacity of the staff to use digital archiving software to log climate data. The initiative improved the forecasting of natural disasters and of the early warning systems (EWS) helping farmers become resilient and better adapt to climate risks. It also influenced the government to formulate evidence-based climate policies and implementation plans. Amongst efforts to achieve responsible production (SDG12), a case study identified the potential of digital technologies in mitigating environmental issues and ensuring the sustainability of natural resources (Hinson et al., 2019). Achieving SDG targets requires consideration of the SDGs within each country's particular context and its digital strategies, including the creation of enabling frameworks with clear financing systems, agricultural transformation, technological innovations and embracing a collaboration of diverse stakeholders (Castro et al., 2021).

Factors limiting digital dissemination of CSA information for smallholder farmers

While digital agronomy service supports to smallholders has significant promise to strengthen extension service delivery in Africa, including for smallholders, there are a range of factors that can act as barriers to digital dissemination of CSA information for smallholder farmers (Table 6). Much hinges on the extent and type of access that smallholders have to digital communication technologies (phones, computers, bandwidth etc.). In the case of video, video training for farmers is considered a good capacity-building strategy (Van Mele, 2008; Zoundji et al., 2024). However, while making videos may seem an easy and cost-effective process, it becomes more challenging in terms of the skills needed for high-quality video production. In addition, disseminating and measuring whether the videos are effective as a training tool, needs strategic planning with consideration of methods, channels and personnel, along with monitoring and evaluation of impact. In general, there are a range of factors and situations that can act as barriers to CSA information dissemination in digital formats (Table 6).

Challenges and opportunities for digital delivery of CSA capacity building

Farmer's perceptions of digital technologies

There can be some negative perceptions around the use of digital technologies for agriculture. For instance, there can be an assumption that digital technologies are primarily for

TABLE 6 Barriers to CSA information dissemination in digital formats.

Factor	Situation	References
Technical support	Some farmers have access to devices but need support from experts. For instance, youth record videos but fail to present them online.	Bentley et al., 2019; Booi et al., 2019; Jolex and Tufa, 2022
Poor quality	Smallholder farmers depend on devices from others sometimes getting assets with limited functionalities such as battery life and poor speed because they have been used for quite a long by previous owners.	Ashraf et al., 2018; Makate, 2019; Latif et al., 2020
Higher Cost	Owning and accessing services from digital devices come with associated costs such as buying, charging, paying for data packages, and understanding the digital systems.	Nzonzo and Mogambi, 2016; Marwa et al., 2020; Simelane et al., 2019
Limited knowledge	Advanced technologies come with different features that require knowledge to use them. For instance, most mobile applications use languages that not all users understand.	Tadesse and Bahiigwa, 2015; Subashini and Fernando, 2017; Tetteh Kwasi Nuer et al., 2018
Poor infrastructure	Electricity access remains a challenge in some rural areas, and where the service is available would require additional costs to charge the devices, and others would need to travel to places with services.	Tetteh Kwasi Nuer et al., 2018; Wahiu et al., 2020; Coggins et al., 2022
Cultural beliefs	Despite fewer digital devices in the household, some women farmers could not access their husband's mobile phones due to cultural norms.	Zossou et al., 2010; Wyche and Olson, 2018

youth leisure activities (such as watching movies or listening to music) and are not useful or appealing tools in the context of agriculture as a business or way of life. Such perceptions may create a negative impression, especially for elderly farmers who may be skeptical of digital technology and whether it can make a difference in the agricultural sector. Therefore, awareness creation amongst all farmers of how to develop, curate and disseminate high-quality digitized training materials is required, alongside scaling of video training initiatives for farmers.

Limited technical capability for the generation of digitized content for CSA training

Technical know-how in relation to digital technologies (including phone technology and features) is an obstacle to many farmers. For instance, in 2013, GSMA's Women Marketing Handbook reported that women's relatively limited ownership and use of mobile phones in developing countries relate to low technical capacity. This low technical capacity is influenced by the inability to read, write and manage some features provided by most mobile phones. Also, additional costs such as buying headsets, data storage, and paying for charging of phones exacerbate the situation. Some areas have witnessed negative cultural beliefs about women capable of owning digital devices (Cariolle, 2021; Coggins et al., 2022).

Privacy and data access

Data control and privacy issues remain as major problems for all digitized content. Where farmers or rural populations provide answers or data, it may often be unclear who owns the primary data or any data derived from the primary data. Personal information may inadvertently be provided to internet or phone operators by end users who are unaware of data protection norms and legislation.

The digital divide between rich and poor

The digital divide remains a barrier to smallholder farmers benefiting from digital technologies, which is exacerbated by illiteracy, infrastructure, facilities, and financial constraints. These factors can prohibit poorer farmers from accessing advisory services from digital channels. In this context, it is worth considering that the internet is declared a human right by the United Nations Special Rapporteur on the Promotion and Protection of the Right to Freedom of Opinion and Expression (La Rue, 2011). Internet access is also recognized in the quest for reducing inequalities, realizing development, and influencing human rights (Skepys, 2012). La Rue (2011) has emphasized that all people must have access to the internet and enjoy the freedom of expression. A survey by the BBC News (2010) that involved more than 27,000 adults in 26 countries indicated that four in five people recognized internet access as a fundamental right.

Business models for the development and dissemination of digitized content for CSA capacity building for smallholder farmers

Developing business models for digitized content generation, curation and delivery is vital to scaling CSA initiatives to realize the possibility of reaching a large population of smallholder farmers, including "last mile" farmers and communities. Partnerships with service providers such as internet providers, search engine proprietors, and other stakeholders are critical to delivering affordable services to farmers.

Internet focal points for rural areas

Telecentres have made a contribution to public internet connectivity in many parts of Africa. However, the fast expansion of mobile phones, has resulted in most users not depending any more on these centers. There can be potential for re-inventing these centers for public consumption with free or low-cost internet charges would be useful, especially for people to access materials related to agricultural innovations. Such access might support disadvantaged groups with limited financial capacity to own digital devices or pay for internet packages with knowledge of agricultural innovations.

Embracing the power of machine learning and AI

With the use of Machine Learning (ML) and AI, digital agronomy has seen unprecedented advancements, as systems are now capable of learning and improving performance without explicit reprogramming (Soori et al., 2023), leading to enhanced efficiency and innovation across multiple sectors (Zong and Guan, 2025). These technologies are transforming data, such as household surveys, soil samples and weather projections, into actionable insights by identifying complex patterns with minimum human intervention. Applications range from predictive analytics for pest and disease outbreaks and real-time crop health monitoring to decision-support tools for optimizing irrigation scheduling and precision fertilizer application (Soori et al., 2024). As we continue to adopt such technologies, their potential to deal with global challenges, from climate change to food insecurity, will become increasingly evident.

Policy frameworks for enabling rural internet access

Governments have a key role in advancing laws and policy frameworks to support smallholder farmers to benefit from the potential of digital technology. In addition, governments have a critical role to play in fostering strategies that encourage access to agricultural information online and offline at an affordable cost. Digital agronomy systems that can effectively reach all farmers can yield major benefits for national agricultural innovation systems by providing platforms for capacity building, upskilling, knowledge exchange, technology access, market data, weather services, insurance services, access to inputs and information on latest policies and regulations. Investment in digital agronomy services can yield significant knock-on benefits to increase the cost-efficiency extension systems and input subsidy programs.

Conclusions

New and innovative approaches for digital technology generation, curation and delivery are essential for scaling CSA to meet targets across Sub-Saharan Africa. Initiatives from multiple organizations (e.g., Access Agriculture, Digital Green, Mkulima Young etc.) are revealing how farmers can access and upskill in relevant agricultural information by employing technological advances like the internet and smartphones. Through these technologies and with the support of extension systems, farmers can engage in peer-to-peer sharing of information for reasons including marketing, finding solutions to problems, advertisements, and training one another.

Despite the need for scaling CSA initiatives across Sub-Saharan Africa, the current status and formats of digitized CSA training materials are insufficient for large-scale training of smallholder farmers across different farming systems, livelihoods, income levels, literacy levels, internet access levels and phone access situations. Key barriers include poor capacity, limited technology, and little support for farmers. Capacity building for peer-to-peer generation of CSA training materials is likely necessary to ensure impacts by young farmers can be generated. It is essential for localization of training across linguistic and cultural contexts can occur.

Youth farmer groups may be possible beachheads for digitized CSA development and dissemination due to their technical capacity and the possibility of content ownership and monetization. For instance, recent innovations have motivated some youths to sell DVDs and show videos about agricultural practices to villages at a low cost. Sustainable business models will require incentives that encourage farmers (especially young farmers) to engage in the generation, curation and delivery (including sale) of high-quality CSA training materials on a pay-per-use basis. Other business models could be borrowed from group systems (e.g., Microfinance, village saving and loans groups, etc.) which use cluster models in which farmers' groups work together to train each other and other groups. Youth groups could also engage with groups of farmers, support them with technical skills, and develop digitized products together.

More extensive and targeted support from service providers such as mobile phone companies and social media platforms such as YouTube, Facebook and Tiktok could make it possible to develop business models for the development of digitized content disseminated via smallholder farmer-oriented channels. For this to occur, action is required on two fronts: (1) the creation and implementation of policies to incentivize digital transformation among smallholder farmers and, (2) the creation of policies to incentivize farmers to develop their own digitized training materials for CSA and to develop business models to generate income or other benefits from their efforts.

Overall, while digital agronomy and CSA services have significant potential to enable the scaling of climate smart agriculture practices across the millions of smallholder farmers, there remains a swathe of significant barriers to scaling digital agronomy in the region. These include the digital divide, types of phones, types of content, business models and digital literacy. Access (including electricity) and affordability (of both phones and access charges). Nonetheless, the rapid expansion of smartphones combined with inventive initiatives to broaden access to high-quality training content indicates that digital agronomy is here to stay, and that it has significant potential to augment the ongoing work of public and private sector extension systems.

Author contributions

MM: Visualization, Writing – original draft, Writing – review & editing, Investigation. LQ: Visualization, Writing – original draft, Writing – review & editing. CV: Investigation, Visualization, Writing – original draft, Writing – review & editing. AF: Writing

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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