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Are digital services the right solution for empowering smallholder farmers? A perspective enlightened by COVID-19 experiences to inform smart IPM

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The COVID-19 pandemic, surprised many through its impact on the food systems, resulting in collapses in the food production value chains and in the integrated pest disease management sector with fatal outcomes in many places. However, the impact of COVID-19 and the digital experience perspective on Integrating Pest Management (IPM) is still yet to be understood. In Africa, the impact was devastating, mostly for the vulnerable smallholder farm households, who were rendered unable to access markets to purchase inputs and sell their produce during the lockdown period. By using a holistic approach the paper reviews different Information and Communications Technologies (ICTs), digitalization, and how this enhanced the capacity of smallholder farmers resilient, and inform their smart-IPM practices in order to improve food systems' amidst climate change during and in the post-COVID-19 period. Different digital modalities were adopted to ensure continuous food production, access to inputs and finances, and selling surplus production among others. This was largely possible by using ICTs to deliver these needed services digitally. The study shares contributions and capacity perspectives of ICTs for empowering smallholder farmers to boost the resilience of their food systems based on COVID-19 successful experiences. Thus digital solutions must be embraced in the delivery of extension service on pest management and good agronomic practices, money transfers for purchasing inputs, receiving payment for sold farm produce, and markets information exchange. These are key avenues through which digital solutions strategically supported smallholder-based food systems through the pandemic.

KEYWORDS

digital services, smallholder farmers, resilience, climate change, smart-IPM

Introduction

The COVID-19 pandemic has caused disruptions to global food supply chains, especially in downstream sectors such as agriculture threatened by climate change corollaries. During the covid 19 period, many low- and middle-income countries have witnessed about a 25% fade in agri-food export. Climate change; variability, uncontrollable and potentially devastating crop pests, and disease outbreaks were among the most problems faced by the agriculture sector in

Africa (Tripathi et al., 2021). The negative effect of COVID-19 created temporary restrictions on physical movement which ultimately made the communication delay in many functionaries involved in farming. Farmers were unable to get the latest information on agricultural markets, and food systems in general (IFAD et al., 2021). Fortunately, all these drawbacks accelerated development trends of digitization of the agricultural sector (Ashton-Hart, 2020; Harring et al., 2020; Romero and Ahamed, 2020; Janssens et al., 2021; Leach et al., 2021). Smartphone applications acted as an important tool for agricultural information dissemination during the pandemic (Pal and Patra, 2021; Bhuvanasri et al., 2022). In such a way, Information and Communications Technologies (ICTs) enabled households to alleviate supply chain movement restrictions, including food-based ones. Particularly, ICTs helped systems become adaptive and more resilient (Kakderi et al., 2021).

The current evolution in ICTs has been immensely diversified and evidenced in many perspectives. For example, many agricultural information and communication technologies (Ag-ICTs) utilize robotic vehicles and drones, computers, radios, Internet services, social media, and mobile applications (Hashem et al., 2021), partly as a direct response to COVID-19 and climate change. Meanwhile, climate change has had wide-ranging effects on the environmental and socio-economic pillars of sustainability; including land and water resources, agriculture and food security (Egan et al., 2021). Indeed, global climate change patterns have changed rainfall patterns, driven up temperatures and consequently amplified water losses, and made some food crops no longer viable where they once were—these have highly challenged the peaceful survival of man and other species and inspired rapid adaptive responses including increased use of harmful synthetic pesticides, which endangers food systems' resilience (Avenyo et al., 2020; Egan et al., 2021).

Resilience is defined by Koskela et al. (2020) as a process whereby people devise means and resources to sustain their wellbeing during challenging times. From an economic system's perspective, resilience is the capacity to reduce vulnerabilities, resist shocks, and recover quickly from setbacks (Meuwissen et al., 2021; Papaioannou, 2021). Resilience then denotes a potential typically activated and observable at the times when a system is hit by stress and shocks. However, during COVID-19, resilience was greatly leveraged on ICTs through enabling; collaboration among partners, food production, and outsourcing (Meuwissen et al., 2021). For pest management as a constant threat to smallholder food production particularly in the developing world, a paradigm shift has occurred over the 60 years of Integrated Pest Management (IPM) toward the notion of Agroecological Crop Protection (ACP). ACP aims to improve ecological health, lessen the impact of climate change, and improve general plant and animal generic conditions, while enabling early detection of pests facilitated by digital platforms (Deguine et al., 2021). As such, the successful household mitigation of adverse effects from pest infestations and resilience under the trying times of climate change and COVID-19 depend on access to timely information, which the adoption of appropriate ICTs for early detection of these pests affords (Marusak et al., 2021).

Given the disruptions in the supply chain of crop and animal products due to COVID-19, further exacerbating the challenges faced in the agricultural sector, the threat to sustainable agricultural livelihoods and food security were eminent (Ozor et al., 2021). COVID-19 related disruptions on livelihoods included: decline in food consumption and income, increased food insecurity (Hevia and Neumeyer, 2020), sharp price spikes, migration, displacement, and decline in remittances (Guadagno, 2020). Therefore, understanding the impact of COVID-19 and how digital solutions alleviated the negative effects is important. Specifically, the study provides a holistic view of interlinkages around how digital services empowered smallholder farmers and facilitated smallholder-based food systems' resilience amidst climate change and COVID-19. The study:

1) Shows the digital services and experiences in agricultural systems during the pandemic and how these impacted smallholder farmers.
2) Reviews how digitalization[1] by ICTs enabled households to stay resilient by applying smart IPM services and what digital agriculture perspectives needed to be promoted in post COVID-19 period to achieve sustainable agriculture systems.
3) Relies on a perspective enlightened by COVID-19 experiences to inform climate smart-IPM practices for managing recoveries from shocks like COVID-19 and similar ones on agriculture.

Understanding the implications of COVID-19 and associated restrictions is necessary in supporting a sustainable post-pandemic recovery for farmers and farming systems. Furthermore, lessons learned from responses to COVID-19 in agriculture are central to informing climate-smart IPM policies that are based on digital solutions. Thus, secondary data was collected for the study. Descriptive research design has been followed for the study according to Ashton-Hart (2020), Ozor et al. (2021) and Bhuvanasri et al. (2022) approches. Generally, researchers went through many valid sources in detail to select secondary data (reviewed articles) used for this study. The next section of the paper presents different kind of digital services experience in agricultural during the pandemic and how these impacted smallholder farmers. Then, the second part presents the digital agriculture perspective and how this could be promoted in post COVID-19 period to achieve sustainable agriculture systems. The perspective is enlightened by COVID-19 experiences to inform climate-smart IPM pratices. Conclusion are presented in the last section.

Case studies of experiences of household use of ICTs and digital services, before and during COVID-19

In the present note, the role of digitalization during the COVID-19 pandemic is addressed. The challenges faced in harnessing digital solutions to cope with the pandemic are discussed, and lessons to be learned for policy responses are also highlighted. Ways in which digitalization can function in recovery, for inclusive and sustainable agriculture development and resilience against potential future shocks, are also explored. Moreover, it is critical to strengthen international cooperation for digitalization that works for a better future (UNCTAD Secretariat, 2022).

The economic and social impact was particularly severe in structurally weak developing countriesbecause of their higher

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[1] Which refers to the tools for digitally collecting, processing, storage, retrieval, and managing and sharing electronic data (Singh et al., 2018).

susceptibility to shocks and lower capacity to adjust to these schocks. Within countries, the crisis has had disproportionate consequences on the most vulnerable and disadvantaged groups—such as low-income households, migrants, informal workers and often women—and economic sectors, such as microenterprises and small and medium-sized enterprises and tourism. The most affected countries, groups and sectors are also characterized by low levels of readiness to engage in and benefit from electronic commerce (e-commerce) and the digital economy (Ashton-Hart, 2020). Following restrictions on movement, individuals, businesses and Governments increasingly "went digital", amid slowing economic activity, thus, the pandemic served as a catalyser of digitalization (Ashton-Hart, 2020).

For exemple in Nigeria, the pandemic caused the country to adopt some technologies such as irrigation and air seeding technology which helped to increase crop yields to levels higher than what it was before the pandemic (Grey et al., 2020). In another perspective for instance, a farmer traditionally noticing any pest infestation in their fields would rush to seek advice from neighbors (in most cases residing in walkable distances) and subsequently implement solutions observed in the neighborhood. Such solutions typically involved using a synthetic pesticide (mimicking or borrowing from the one the neighbors used) and sourced from the village farm inputs sellers (Sarkar et al., 2021). Besides the often prohibitive expense of this for smallholders (leading to disadvantageous borrowing or no pest intervention), inability to read warning labels on synthetic pesticides exposed farmers and environments to increased harms. Furthermore, under COVID-19, farmers were faced with physical distance barriers to access technical advice from extension agents or authorized technical persons. ICTs bridged these distances and eased movement restrictions and often assisted in proper identification and description of the pests (Sarkar et al., 2021). While this supported subsequent pesticide prescription (and potentially proper guidance on where and how to use such harmful materials safely) (Saleh, 2020; Sarkar et al., 2021), information about safer, nonsynthetic pest management materials could also be accessed. Specifically, a nonsynthetic pesticide made from neem tree seeds is a safer, less expensive, and environmentally non-harmful alternative with existing digital (ICTs) support in educational videos (SAWBO, 2017). In one community in Burkina Faso, farmers who had learned of the neem seed alternative, planted the otherwise not locally available neem trees in their community, so that they could produce the safer pesticide (SAWBO, 2021).

Similarly, upon realizing the symptoms of damage from pests, farmers might rush to the nearby extension agents for field inspections and advice (if available). However, the physical movement restrictions of COVID-19 lockdowns made access to field visits very difficult, if not impossible (Deguine et al., 2021). Here again, the use of digital services gave farmers access to better information (even under restrictions on movement) so as not to rush into risky decision-making without proper technical guidance. For example, Sheahan et al. (2017) elaborated that while the use of synthetic pesticides can increase crop yields, it is also strongly associated with accidental negative effects on both environmental and human health, leading to increased social health-related costs and time lost away from farm work due to sicknesses associated with pesticide-use. In that sense, it is not clear if the gain (in crop yield) is not offset by these losses.

Many smallholder farmers in Tanzania have strong international market connections, typically selling crops such as spices, yams, bananas and sugarcane to buyers from Kenya, India and Tanzania (Dar es Salaam, Pemba and Zanzibar). With the closure of international borders between Tanzania and neighboring countries and enforcement of domestic travel restrictions, market competition declined as buyers could not reach farms (Ashton-Hart, 2020). Farmers were consequently faced with limited selling options,with some forced to sell spices locally at severely reduced prices. Concern and suspicion of travelers also affected farmers' willingness to receive potential buyers (Tripathi et al., 2021).

In South Africa, smallholder farmers cultivating fresh and perishable products (such as fruits, vegetables and dairy) for local markets, struggled to sell produce due to the demand fallout and closure of local informal markets (Ashton-Hart, 2020). These farmers had to store perishable farm products on the farm in anticipation of the reopening of informal markets, which led to high post-harvest losses and increased storage costs. Similarly, large-scale commercial apple farmers also incurred losses as demand and prices for apples in the export market crashed after international border restrictions (R2.5 [Rands] per kg in 2020 compared with R13 in 2016) (Ayanlade and Radeny, 2020). In addition to the price crash, such additional packaging and transport costs drastically reduced farmers' profit margins, with implications for the sustainability of future harvests (Tripathi et al., 2021). Furthermore, in South Africa, climatic challenges, followed by COVID-19, created compounded issues, planting unusually late in the season, at the end of November 2019, following the rains that arrived mid-month. Delayed planting was followed by early onset of frost, severely reducing the growing season (Ayanlade and Radeny, 2020). This required farmers to use chemical fertilizers and pesticides, livestock and short-season crop varieties, subsequently squeezing profit margins. Furthermore, lack of water for irrigating crops and pasture as major weather-related problems, alongside negative impacts from crop pests and diseases, which became worse due to lack of access to inputs (Ashton-Hart, 2020). Many smallholders and emerging farmers voiced concern for future farm productivity and resultant food shortages over the following 1–2 years due to longer-term compounded impacts of COVID-19.

In west Africa, the fall armyworm (FAW) became a dangerous invasive pest, now detected in more than forty countries in sub Sahara Africa (SSA) (Guimapi et al., 2022), and documented as feeding on 353 host plants with an estimated loss of 8.3 to 20.6 million metric tons per year in twelve of Africa's maize producing countries (Houngbo et al., 2020). For pest control practitioners, deployment of curative strategies can only be effective with vigilant surveillance, monitoring, and scouting of FAW infestation levels, which ICTs both supported and enabled (Bello-Bravo et al., 2018b; Ahissou et al., 2021; Høye et al., 2021; Tepa-Yotto et al., 2021). Indeed the livelihoods of smallholder farmers are always at stake due to the devastating damage caused by pests, especially those whose damages cover a wider area in a short time like the FAW (Ahissou et al., 2021; Egan et al., 2021). Demand for many other occupations may decline through 2030, including customer service and sales positions, food service jobs, and office support roles, such as administrative assistants and bookkeepers. The disruption is likely to have the biggest impact on low-wage jobs that have served as a safety net for displaced worker in the past (Lund et al., 2021).

Although digital services may be difficult to use by low-literate farmers at times, the Farmer Interface Application (FIA) developed by the Institute of Tropical Agriculture (IITA) and partners is one example that has shown that ICTs can be useful in pest management, especially for informing farmers on timely interventions on pesticide use (Tepa-Yotto et al., 2021). While combating invasive pests was made more difficult with restrictions imposed by COVID-19, the disruption to food systems exposed opportunities that could be exploited by connecting local production and consumption communities using ICTs. That is, the pandemic uncovered interconnected vulnerabilities linking livelihoods and food distribution as countless suppliers and vendors around the world experienced food losses because they could not market their food or hours were restricted (Blay-Palmer et al., 2021).

With ICTs, it became possible to organize farm inputs and food orders, with subsequent deliveries accompanied by electronic payments for these supplies. It must be pointed out here that traditional telephone is an ICT, which has long bridged distance gaps between farmers, markets, and extension agents. The mobile phone has radically changed what telephony can accomplish; as a COVID-19 example, extension agents could be reached by mobile phone, even when movement restrictions force them to remain out of the office and away from their landlines. Mobile phones have also, since 2015–2017, become the leading access device-type for obtaining digital information (Bello-Bravo et al., 2021). Equally, radio and television are traditional sources of ICT information (often as community members would gather around a single radio or TV). While Internet may be available through computers, radio and television information is more often supplemented or accessible *via* mobile phones. During COVID-19, accessibility to traditional forms of ICT (telephone, radio, television) were facilitated by mobile phones (when affordable), even in lockdowns. In general, ICTs can enable faster access to updated data from farming households, thus enabling appropriate interventions tailored to a food system's current needs. For instance, Agamile (2022) and Tortorella et al. (2022) used a High-Frequency Phone Surveys (HFPS) ICT strategy to collect household consumption data at monthly intervals during the COVID-19 lockdown, because face-to-face interviews could not be used. Agamile (2022), indicated that indeed the lockdown had induced income losses significantly, reduced access to farm-inputs, and increased incidences of food insecurity. These findings fostered government initiatives to support food consumption for the vulnerable communities (especially those in urban slums).

Furthermore, global border closures, production shutdown, and restricted exports resulted in inflationary tendencies for different food and non-food commodities, which affected smallholder farmers globally Quayson et al., 2020. For instance, in Ghana, cocoa smallholder farmers were the hardest hit with especially limited access to markets due to the disruption of the international cocoa supply chain. Cocoa farmers would also find it difficult to get information from extension workers on pest management and good agronomic practices, who previously delivered it physically. However, the use of digital services like drones, sensors, climate-smart agriculture services accessed by mobile phones, and other ICTs opened up possibilities for smallholder farmers to increase their households' resilience and minimize the negative impacts of pests, climate change, and COVID-19 Quayson et al., 2020. In other African countries with massive exposure to digital innovations, where market linkages were treated to COVID-19 movement restrictions, mobile phones have dramatically enhanced financial inclusions and transactions, relying on platforms such as MPESA in Kenya, MTN-MOMO in Uganda, Agrikore in Nigeria, and others (Quayson et al., 2020; Blay-Palmer et al., 2021; Agamile, 2022).

In another perspective, school closures due to COVID-19 threatened educational delays, particularly for students from low-income households without access to virtual learning facilities or poor infrastructures for them (Ingutia, 2021). Nevertheless, ICTs facilitated and supported remote learning (Kamal, 2020), even in countries worst hit by the pandemic (e.g., India, the United States, Brazil, Russia, and Mexico). During the pandemic, the use of digital technologies for teaching and learning significantly grew in speed and scale (Kamal, 2020). For instance, Asanov et al. (2021) noted that learners were engaging in remote learning using different ICT tools mostly the Internet *via* phones (74%) or a computer or tablet (59%). Moreover, those who didn't have easy access to Internet or phones or computers also participated in remote learning *via* educational programs broadcast by television. These modalities were also possible for smallholder farmers with the use of digital solutions to access inputs, detect pests and access markets (Quayson et al., 2020; Blay-Palmer et al., 2021; Tepa-Yotto et al., 2021). Nonetheless, the speed and affordances of digitalization, and presuppositions about who has (or could have) remote access for education, has accidentally left an uncounted number of students out of the picture (Doyle, 2020; Reich and Mehta, 2020; HRW, 2021). For instance, in Botswana, local farmers were well acquainted with conventional farming techniques lacked the knowledge of contemporary farming techniques. Thus, academic institutions like the Botswana University of Agriculture and Natural Resources (BUAN) through its Centre for In-service and Continuing Education (CICE), offered short courses and trained farmers on use of ICTs in agriculture (Ashton-Hart, 2020).

In business terms, COVID-19 transformed daily practices to the extent that businesses adopted ICTs as a way to stay afloat during lockdowns. Because of the disruptive nature of the pandemic, COVID-19 compelled rapid transformations in business processes and operational practices; home-delivery services skyrocketed along with the use of digital communication platforms (i.e., Zoom, WhatsApp, or MS Teams) for conducting meetings (Kamal, 2020). In places transitioning to post-COVID-19, the radical increase in use of digital technologies, and diffusion of electronic information systems became more permanent. Thus, ICTs also supported, boosted, and sometimes fostered continuity of home-based businesses during COVID-19, affording ensuring resilience in terms of sustained income flow. For instance, Saleh (2020) noted that Internet-based ICTs and social media usually were used to communicate (through mobile phones) directly with customers, receive orders, advertise products and services, do payments, and so on. This allowed businesses to manage resources effectively, make faster communication within the firm and with customers thus, in-principle increasing business productivity, decreasing physical transaction costs, advertise cheaply, deliver certain products and services more quickly, even within home-based business contexts (Saleh, 2020).

In small and medium enterprises (SMEs) contexts, which can be pivotal for providing extra income support for smallholder farming households that supply SMEs with raw materials, profitability was greatly affected by the pandemic (Zutshi et al., 2021). SME sustainability became extremely difficult, and many of them collapsed. However, some were able to adopt resilient ICT strategies (including digital services) for accessing (sometimes new) pathways for obtaining raw materials from farmers while reaching out to consumers, thus enabling some SMEs to survive despite making little to no profit (Musa and Aifuwa, 2020; Love et al., 2021; Panzone et al., 2021). These patterns are now habitual and will remain in place post-pandemic. As such, these practices and supply-chain changes are potentially accessible to smallholder producers and consumers. Indeed, rural poor farm households were tested to the extreme by COVID-19 because they were generally cut-off physically and digitally from the market structures. However, the spread of ICTs (again, especially mobile phones) opened channels to communicate, access remittances, and make business payments, transforming the challenging scenario for rural folk from hopeless to a potential for survival through money accessed *via* mobile phone money services for food, farm inputs (seeds and pesticides), and other necessities (e.g., medicine) (Quayson et al., 2020; Saleh, 2020; Rajkhowa and Qaim, 2022).

In more urban areas, the concept of smart-city solutions accelerated, fueling the use of smart technologies and its diverse components (including Artificial Intelligence, machine learning, blockchain, autonomous vehicles, 5G, virtual reality, big data analytics, cloud computing, and others (Høye et al., 2021; Sharifi et al., 2021). In agriculture, the contribution of nature-smart city and the defense of biodiversity have a direct positive impact on the living environment such as fighting air pollution and mitigating the effects of current climate change, but also its consequences such as drought. Therefore, it requires knowing how to control feeding in urban agriculture, new agronomic techniques, pest and diseases management using the more accessible means, the digital solutions. For instance, in Niger, the strategic plan has four main pillars, namely, e-government services, the creation of a "Technopole" (a city of innovation and technology), the promotion of digital technology and the Smart Villages project (Peckham et al., 2020). Moreover, in December 2020, the country launched the Smart Villages Project for Rural Growth and Digital Inclusion (PVI) to leverage digital technology to develop the agricultural sector, through establishing digital payments, e-extension services, and data platforms for farmers and ranchers (Ashton-Hart, 2020). In Angola, Smart Villages were established to provide sustainable renewable energy services to rural communities. This initiative enabled digital connectivity through ICTs where smallholder farmers could more effectively use mobile phones and other electronic gadgets in times of restrictions on human contacts such as the COVID-19 period (Ashton-Hart, 2020). Therefore, these ICT-enabled technologies and their integration with the physical infrastructure were pivotal for enabling the (during-disaster) absorption and (post-disaster) recovery capacities of different cities during COVID-19 (Sharifi et al., 2021). For example, the 5G technology greatly improved the speed, efficiency, and flexibility of the pandemic-related innovation (including supply chain management, telemedicine, self-isolation) while affording a swift implementation of broader health services (Siriwardhana et al., 2021). Extending these benefits to people living in peri-urban and non-urban areas is imperative if they are to become sustainable.

In terms of food production systems, particularly for smallholder farm households, although digital services can often be very expensive for smallholder farmers and cannot feasibly be used on farm fields at large scales, ICTs have been developed to help boost green crop technologies (e.g., the use of biosensors and chemo sensors to detect chemical information in the ecological system as an alternative to the use of pesticides) (Cardim et al., 2020; Ivaskovic et al., 2021). Indeed, pro-smallholder farmers, user-friendly IPM systems have been developed to improve the management of insect pests on smallholder farmer fields (Cardim et al., 2020). These IPM digital services aim to reduce the overall use of pesticides through more precise applications as necessary. Most of these IPM-based, digital-services technologies are still not readily applicable at-scale to the majority of smallholder farmers due to long lags in producing desirable results; nonetheless, developments are underway to innovate smallholder-friendly basic pest detection systems using mobile applications like FIA, radar technologies monitoring pest migration, video equipment to observe flying insects, and thermal infrared imaging among others, for the future and are not restricted only to immediate needs (Cardim et al., 2020; Høye et al., 2021; Liu and Wang, 2021; Tepa-Yotto et al., 2021). Pending these developments, the use of digitally based educational ICTs to inform farmers about cost-effective agricultural innovations that already exist and can be implemented right now.

Furthermore, deep learning technologies have been widely deployed for plant pathology but are still in the initial stages of use in agricultural entomology (Mittal et al., 2020). However, ICT-assisted deep learning-based endeavors anticipate breakthroughs for studying and monitoring pests *via* mobile Apps (including for detection and classification of different invasive pests like FAW) (Karar et al., 2021; Sarkar et al., 2021; Tepa-Yotto et al., 2021). Digital services aided by ICTs have already helped researchers and extension scientists to analyze data and help generate, document, and disseminate scientific evidence on pests management to farmers and other stakeholders with the aid of the Internet services (Bello-Bravo et al., 2018b; Singh et al., 2018).

Summary of perspectives regarding IPM

Several digital technological recommendations have been made to help smallholder farmers continuity, especially in developing nations. The feasibility of these activities may be called into rightfully so, hence there must be operational and economic feasibility. In Ghana and Nigeria, these efforts are occurring. But, operational feasibility can also be managed by nongovernmental organizations, forexaple Smart Villages or for-profit corporate partners. The for-profit partnerships may require some investments in training, yet the benefits of such training can be more reliable and inexpensive sourcing of material such as cocoa (Ashton-Hart, 2020). The benefits can also be social and environmental from better operations. The reputation and image of these larger organizations can improve if the smallholder farmers' situation improves. This investment can improve competitiveness for some basic commodity value chains. Relatedly, economic feasibility must also occur. In many cases, farmers may have access to some mobile phones and rudimentary computing capabilities. The additional costs may be the development of applications. Forexample, there are some initiatives for e-government and digital government strategies, where governments are pushing toward e-government services (Echazarra, 2018).

The COVID-19 pandemic movement restrictions as part of the control measures put in place by several countries had implications on food security, as movement restrictions coincided with planting periods for most staple crops, thus exacerbating food insecurity

(Ashton-Hart, 2020). Achieving adequate food supply required developing better policies to confront the challenge of reducing hunger post COVID-19. The lessons learned after COVID-19 crisis will be very important for particularly developing countries to rethink their strategies for sustainable economic growth, (Ayanlade and Radeny, 2020). For instance, in some African countries with massive exposure to digital innovation, mobile phones have dramatically enhanced financial transactions such as MPESA in Kenya and Agrikore in Nigeria, thus eliminated all problems associated with physical transactions, especially during the pandemic, where handling of cash posed a threat to the human life. It also eradicated acts of corruption and theft, thereby establishing a high sense of confidence and accountability in food systems operations. In Ghana, the Blockchain Technology digital solutions to connect farmers to markets through agents called purchasing clerks (PCs). These PCs work on commission and deal directly with farmers, and their transactions were monitored electronically, thus reducing the possibility of corruption and cheating against smallholder farmers (Ayanlade and Radeny, 2020).

With the availability of the internet and cheaper mobile devices, digital applications for communication in for instance Sub Sahara Africa (SSA) are increasing rapidly. Digital solutions are playing an increasingly important role in transforming agricultural ecosystems and value chains, and strengthening food supply systems, particularly in a post-COVID world (Ayanlade and Radeny, 2020). A digitized marketing system, for example, where buyers, sellers and consumers can communicate directly, could reduce reliance on conventional markets and provide greater adaptability in buyer-producer access. There is, therefore, a need to focus on building institutional digital capacity by, for example, providing training to extension officers and farmers in guiding the community marketing schemes and collaborating with farmer groups to use ICTs to identify, and participate fully in competitive agri-food markets (Tripathi et al., 2021).

In a labor perspective, COVID-19 did not only worsen the existing labor shortage, but also caused tremendous changes in the production processes, trade systems, and consumer behaviors. During the pandemic, Krishnan et al. (2021) identified the areas of innovation critical to building a healthier and more sustainable food system, and those areas that would be most impacted by the pandemic. Krishnan's team delved deep into pandemic economic history and focused on the structural and cyclical undercurrents sculpting the post-pandemic worlds. Among the five technological areas that they found essential post-pandemics was the food and agriculture digitization (Tsay et al., 2021).

Regarding managing pests, in much of the developing world, especially in SSA, farmer decisions to spray against pests is season-based or dependent on *ad hoc* visual evidence of pest symptoms in farm fields. This in turn results in inappropriate targeting and severe human and environmental health impacts (Sarkar et al., 2021). More disturbingly, this trend has been aggravated by climate change, which has in some instances favored proliferation of pests, thus forcing farmers to over-use chemical pesticides as a remedy to yield losses attributed to pest infestations (Zinyemba et al., 2021). The fundamental tension here is the perception that synthetic pesticides are the only (or the only effective) form of pest control. These perceptions, as is now documented, look at crop yields as the only variable, without taking account of the broader socioeconomic and environmental costs of synthetic pesticides. As such, ICT-based educational approaches are imperative for changing these perceptions, so that farmers who are faced with concerns about supporting their families and livelihoods think more broadly about the system-wide costs of synthetic pesticides and not only how much income they can expect from better safeguarded crops. That is, as farmers understand that the marginal increases of income (from using synthetic pesticides) are eaten up by increased input costs and decreased health (for themselves and their family, and any attendant healthcare costs, if they access healthcare at all). Thus it is more apparent that slightly smaller crop yields actually yield better overall livelihoods (Bello-Bravo and Pittendrigh, 2018). Under earlier versions of IPM, the use of synthetic pesticides was curtailed in farmer field schools (FFS), in which extension agents advised farmers on basic ecological principles such that farmers could ably assess necessary damage thresholds and know when to use pesticides appropriately or not (Bello-Bravo and Pittendrigh, 2018). However, FFS based on physical attendance of trainers and farmers are resource intensive, not possible during conditions like COVID-19, usually under-manned, and thus not sufficient for reaching out to all farm households. To this day, farm households continue to experience extreme shortages of access to extension agents and tools for enabling informed decision-making about available, cost-effective nonsynthetic alternatives to synthetic pesticides (Bello-Bravo and Pittendrigh, 2018; Sarkar et al., 2021; Zinyemba et al., 2021).

On the other hand, FFS lack good identification of pest organisms, especially when the pests are in their damaging stages (Zinyemba et al., 2021). A clear example is that of the fall armyworm populations proliferation in SSA, which caught maize farmers by surprise without any comparable previous experience with a pest producing similar maize damage patterns. Subsequently, maize farmers only became aware of the pest invasion after the damage was largely accomplished, and even more so when the current season's yield was destroyed (Zinyemba et al., 2021). In all of these cases unfortunately, the use of synthetic pesticide was too late to yield any suppressive impact on the pest and wound up a waste of time, money, and effort and an unnecessary load on the environment. Farmers would have had to have been aware of the destructive early stages of FAW (eggs and larvae), which illustrates the appropriate entry point for farmer sensitization and empowerment, which ICT digital services with wider reach could have accomplished (Gebreziher et al., 2021; Tepa-Yotto et al., 2021; Tansuchat et al., 2022).

Fortunately, recent innovations may enable accurate pest diagnostics especially using artificial intelligence (AI) (Høye et al., 2021; Karar et al., 2021; Liu and Wang, 2021) combined with automated monitoring tools (Cardim et al., 2020) and nano sensors (Ivaskovic et al., 2021). Farmers can access accurate information from these tools for diagnosis and identification of pest problems and their fields. These stand to be a great addition to the future IPM apparatus, when they become available and operational at farm level. In the meantime, however, smallholder farmers must be sufficiently helped against the double burden of current and new invasive pests, especially when supposedly "innovative" pesticides hold out ineffective and unsafe synthetic products to smallholders (Ahissou et al., 2021). Steps have already been taken to educate and empower farmers with and in digital tools for taking correct actions for pest detection and management (e.g., the FIA app documented in detecting early-stage fall armyworm using GPS technology to determine infestation locations and intervention magnitudes required) (Tepa-Yotto et al., 2021). Smallholder-farmer user-friendly apps like FIA have also been designed with a gender-inclusive mode aimed at minimizing (rather than exacerbating) gender inequalities. A focus on gender is critically necessary in SSA, where women and girls are major participants in agricultural production and yet still experience barriers to educational information (such as not being allowed to sit in the same places with men during capacitation programs and extension services delivery) (Ragasa et al., 2013).

From an international perspective, even before the pandemic, ICTs for agriculture were spreading rapidly. In recent years, ICT solutions, in that farmers and fishermen need access to up-to-date information to improve their livelihoods (IFAD et al., 2021). For instance, in 2020, as the COVID-19 pandemic progressed, people in the Pacific Islands, found that the usual food supply chains were no longer working, and digital solutions in agriculture suddenly had a new role to play (IFAD et al., 2021). Also, a joint report by Google and the International Finance Corporation (IFC) estimates that the digital economy has the potential to reach 5.2 percent of the Africa's GDP by 2025, which would contribute $180 billion to its economy (Hensher et al., 2021; Sinha et al., 2022). This would particularly benefit women, who on average earn less money than men and are more likely to engage in unpaid work. Factors such as employment discrimination, the gender pay gap, inability to make financial decisions, the need to care for children, and unpaid domestic work, as well as being excluded from the formal economy, significantly limit women's access to better pay, a gap that can be closed by digital solutions. However, as the sophistication and functionality of ICTs increase, the cost also increases, further limiting access for potential new users and the functionality available to current users (Intel, Global Development Advisors, and Globe Scan, 2012). Thus, the digital gender gap may widen as technology evolves and its cost increases (NNie et al., 2015). Some studies have shown that women, especially older women, are less likely than men to be aware of the benefits the Internet offers, and therefore more likely to think they "don't need it" or "don't want it" (Fallows, 2005). Limited education often leads a person to be suspicious of digital devices and unaware of the benefits that ICT might offer. A study based on interviews and surveys of 2,200 women and girls living in urban and peri-urban areas in Egypt, India, Mexico, and Uganda found that 25 percent of women without access to the Internet did not want to use it, and almost all felt that the Internet had nothing to offer them (Intel, Global Development Advisors, and Globe Scan, 2012).

Conclusions and next steps

Generally, COVID-19 has exposed farmers to high levels of income insecurity, underlining the importance of building resilience among farming households. Agriculture extension services have a crucial role to play in this context toward enhancing agricultural productivity and ensuring food security as economies struggle to recover from the pandemic. In doing so, it is important that farming households continue playing their crucial role in agricultural systems effectively, moreso by using modern climate-smart IPM tools, alongside any othertraditional innovations already available. This can become easier if it is ICT-based relying on system-customized digital solutions, which are inclusive of everyone. With school closures, uneven access to online home schooling and economic pressure on families, progress in education, especially for girls particularly experienced an enormous setback. Similarly, women have not been able to capitalize on digitalization, as the pandemic has exposed significant existing gender digital divides. Such divide and similar ones must not continue if digital solutions must be inclusive of all farmers especially regarding adoption of climate-smart IPM (Tansuchat et al., 2022). In relation to policies, FAO noted that increasing access to and use of ICTs can benefit smallholder farmers and farming communities by: facilitating access to relevant nutrition and agricultural information; increasing access to financial services for rural communities; increasing access to insurance and other tools to better manage risk; and providing new business opportunities in rural areas. Increasing resilience to shocks is also the goal of ICTs that locate weather forecasts *via* SMS messages and mobile applications. For instance, the Mfarms program (which operates in Ghana, Kenya, Benin, Côte d'Ivoire, Senegal, and Malawi) worked in cooperation with NASA to release an application that provides smallholder farmers with updated satellite weather data and evidence-based weather tools for agricultural productionSuch corporation can be scaled in other SSA countries.

More specifically, in this article, we shed light on digital transformations necessary to build resilient post-COVID-19 smallholder-based food systemsgrounded on climate-smart IPM innovations laveraged on digital solutions. This (post-pandemic) is the best time to adopt these climate-smart IPM technologies laveraging digital solutions to benefit the bottom of the pyramid smallholder agricultural supply chains. Nevertheless, some pertinent issues need to be considered to make these transformations successful. The first concern is how to utilize existing IPM technologies and merge these with emergent ones that are incorporated with digital inclusion. Utilization must be sorted. Secondly, the roles and effectiveness of various stakeholders and institutions in the digital transformation, is not clear and this must also be harmonized, to avoid conflict among stakeholders. For example, digital inclusion can increase productivity and resilience while reducing the vulnerability of hundreds of millions of smallholder farmers, thus affecting given stakeholders, respectively (Quayson et al., 2020). Therefore, this study highlights the an unequivocal need for creating more resilient and inclusive agriculture systems that can ensure that all stakeholders benefit equally from scaled digital solutions around climate-mart IPM for pest management, and other innovations (Alvi et al., 2021).

Taking this holistic view, smart pest management approaches based on sound scientific data will necessarily be effective when correctly deployed in appropriate contexts; it is thus more likely that this will involve no use of synthetic pesticides (Egan et al., 2021). However, to effectively transition to smart-strategy IPM using nonsynthetic insect control methods (whether through pesticides or other techniques), digital technologies and gender-inclusive IPM approaches (both educationally and in practice) become indispensible for integrating current and future generation populations (youths) in climate-resilient and disaster-resilient IPM practices. Existing changes that can be made to the infrastructure must also be explored for the immediate enhancement of food security. For example, certain sectors of economies not only did not experience livelihood impacts during COVID-19 (e.g., freelance, Internet-based at-home workers) but may have accumulated savings due to movement restrictions (by spending less money). This is already a form of pandemic-resilience, which demonstrates the possibility of extending "what makes that resilience work" to other economic sectors. For example, at-home food delivery (e.g., Door Dash, Grub Hub, and the like) vastly extended digitalization of the dining sector of the economy and made it possible to get food to people (at a fee) despite movement restrictions. An analogous service to transport smallholders' crops (safely and in accordance with any movement protocols) to digital or analog markets would be another aspect to add to a holistic approach to food security (pending any smart climate or smart agriculture innovations, however many years off they are). It is vitally important to remember these "analog" variants as well, since all ICTs are dependent on a stable supply of electricity; in a context where an electrical grid collapses indefinitely, no aspect of support offered by ICTs would remain. Gasoline-powered generators and solar-powered chargers are two such options.

Furthermore, public financial investments must prioritize consistent plant health research other than *ad hoc* temporary projects that do not advance beyond pilot stages of IPM technological transfers to farmers. Africa and IPM innovators alike can learn from successful experiences and lessons gained from elsewhere, particularly taking a solid example of the useful digital innovations' experiences of the COVID-19 pandemic and traditional/indigenous practices, to develop effective, holistic, cost-effective digital-based IPM implementations with "virtuous feedback" loops for sustainable and diversified agriculture. This in contrasts to stagnating in "pernicious feedback" loops as elaborated by Mortensen and Smith (2020), which perpetuate and keep in place unworkable practices that maintain a disadvantageous status quo. To achieve these envisioned successes, a proper, functioning, and empowering policy environment is helpful (Sheahan et al., 2017; Egan et al., 2021), but successes are possible at the community and grassroots level if stable or funded policy is not available. For example, ICT-based educational curricula are available to local change agents for their educational projects regardless of national-level shortages of funding and available of extension agents (Bello-Bravo and Pittendrigh, 2018). In all of these recommendations, our primary emphasis is that whatever the future promises to hold, it is already possible and necessary, right now, to make radically innovative agricultural offerings available to smallholder farmers through ICT-enabled educational means. These means are gender non-exclusive and have a demonstrated capacity to impart learning gains regardless of participants' age, geographic isolation, educational or technological literacy levels, or socioeconomic status (Bello-Bravo et al., 2018a).

Author contributions

Conceptualization: HS, GT-Y, and MT. Methodology, formal reviews, and writing—original draft preparation: HS, YK, and MT. Validation, writing—review and editing, and visualization: HS, GT-Y, AA, KT, BP, YK, and MT. Resources and funding acquisition: GT-Y, AA, KT, BP, and MT. Data curation: HS and YK. All authors have read and agreed to the submitted version of the manuscript.

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Conflict of interest

YK was employed by LADS Agricultural Research Consult.

The remaining 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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