ABSTRACT
In sub-Saharan Africa, mass rural-urban migration negatively affects the agriculture sector that accounts for about 23% of the GDP and employs over 60% of the population. Together with a rapidly changing climate, unplanned urbanization poses serious threats to Africa’s agriculture sector with the risk of chronic food shortages in the future. To stem this tide, it is imperative to systematically assess the unplanned urbanization trend from a socio-economic perspective and distill the broader implication for sustainable urban farming within the context of climate change in the region. The potentials of digitalization as a tool for transformative adaptation to climate change and enabler of sustainable development in different domains, including agriculture, are beginning to emerge. However, most studies are based on data from Asia, Europe, North America, and Oceania. There is minimal documentation of current applications and prospects of digitalization for sustainable agricultural practices in Africa, particularly in an increasingly urbanized era. Thus, this study addresses this need by evaluating the potentials of digitalization to enable sustainable farming in the face of unprecedented climate change constraints in Africa and minimize the negative impacts of urbanization on agriculture. Through a desk research approach, the present study explores the challenges to digital farming in Africa despite its successful implementation in the global North. Drawing lessons from successful case-studies worldwide, we suggest possible pathways to overcome the challenges and implement localized digitalization approaches to strengthen preventive action against climate risks, enhance disaster preparedness, and aid effective planning and management of agriculture practices. Integrating agriculture into the city via digital urban farming is crucial for long-term food security and
creating appealing clean-tech jobs for a large number of new immigrants, thereby supporting African cities’ resilience and sustainable development.

1. Introduction

Sub-Saharan Africa (SSA) is home to about 13% of the world population, and agriculture plays a significant role in the region’s socio-economic development (OECD/FAO 2016a). The sector employs more than half of the total workforce, contributes about 15% of the region’s GDP and more than 40% of exports (OECD/FAO 2016a). Despite the projection of agriculture development in the region to rise further by 2.6% per annum (OECD/FAO 2016a), the food security and the potential of agricultural productivity in reducing poverty and promoting economic growth are threatened by socio-economic and environmental challenges including climate change and rapid urbanization (Van Etten et al. 2019). Thus, research and public policies are needed to reposition the agriculture sector to address the region’s contemporary urbanization challenges.

Urbanization is impacting agricultural development in SSA in multiple ways. The mass movement of people from rural areas where farming is predominantly practiced causes workforce shortages, while unplanned urbanization exacerbates climate change, affecting agriculture production. Africa has one of the world’s fastest urbanizing rates, with the proportion of urban residents estimated to rise from 40% in 2018 to 59% by 2050 (Saghir and Santoro 2018). Urbanization can lead to employment diversification and shift from agricultural to non-agricultural activities when rural dwellers abandon farming and migrate to cities (Hasan et al., 2020). According to the Food and Agriculture Organization of the United Nations (OECD/FAO (2016a), the population in Sub-Saharan Africa could double by 2050, increasing annual agricultural consumption by 2.8% until 2030, and by 2.0% from 2030 to 2050. This rapid population growth and urbanization imply that food production will grow more slowly than demand resulting to food scarcity and increased malnutrition.

In SSA, climate change, urbanization, and population growth are aggravating the challenges to agricultural development. Low precipitation between 1990 and 2013 resulted in a record 43% of global drought events happening in SSA. This severely impacted agriculture output due to the predominance of rainfed agriculture and pastured livestock systems in the region (OECD/FAO 2016b). Climate change projections indicate further warming trends, frequent extreme heat events, aridity, and change in rainfall patterns (OECD/FAO 2016b; Serdeczny et al. 2017). There is also a possibility of massive flooding due to the projected rising sea-level (Tella and Balogun 2020) that could reach about one metre by the end of this century under a 4°C warming scenario (IPCC 2014). Future climate change may present additional challenge for agricultural development in SSA, particularly the rainfed agricultural system that supports the largest share of food production and other livelihoods (Serdeczny et al. 2017). Their impacts on agriculture could seriously worsen livelihood conditions, escalate poverty, and increase food insecurity in the region.

Sustaining food security within this growing face of climate change and urbanization challenges in the region can bed through several measures. These measures include technology adoption to incentivize large scale farming in urban areas, facilitating access
to irrigation systems, improving digital farming practices and infrastructure; and implementing favourable policies to support digitalization for transformative adaptation to climate change in farming (OECD/FAO 2016b). Although most of these proposed solutions are gradually being implemented in parts of Europe, North America, and Asia (Balogun et al. 2020), studies on using digitalization to accelerate sustainable farming practices in Africa are scarce. Moreover, many people consider agriculture as an endeavour exclusive to rural areas and some city authorities even consider urban farming unhealthy and hindrance to city development (Padgham et al. 2015; Nkumah 2019).

Nonetheless, some recent studies have discovered the contrary. In a recent study of the future of agriculture in Africa, Nkumah (2019) stresses the possibility of leveraging urbanization in Africa to push for urban farming to address food insecurities and climate change challenges. Similarly, digitalization is expected to radically improve farm management systems and value chains, build resilience to labour shortage and climate change (Poppe et al. 2013; Knierim et al. 2019). Although the benefits of urbanization and the potentials of digitalization to accelerate transformative adaptation to climate change and ensure farming sustainability are anticipated within the African agricultural space, systematic data-driven analysis and comprehensive documentation have yet to take place. Therefore, this study aims to address this gap through the following objectives:

1. Evaluate the potentials of digitalization to enable sustainable farming in Africa
2. Explore the challenges to digital farming in Africa

The rest of the paper is structured as follows. Section 2 introduces transformative adaptation and discusses the relevance of digitalization to transformative adaptation and sustainability in agriculture, particularly from the “innovation” context. Section 3 provides a detailed explanation of digitalization in agriculture in general and digital urban farming. Section 4 presents various cases of digitalization in farming from around the world. The methodological approach adopted to identify and analyse specific case studies of digital farming in Africa is discussed in Section 5, and Section 6 presents key findings from the study’s assessment. In Section 7, results from the case studies are analysed and discussed with recommendations on future pathways, followed by the study’s conclusion in Section 8.

2. Transformative adaptation

A key determinant of sustainability in agriculture is the ability to effectively cope with and adapt to climate change challenges that usually disrupt productive farming processes. Responses to climate change events can be categorized as coping, incremental adaptation, or transformative adaptation (Fedele et al. 2019). Coping strategies are reactive responses to reduce the impacts of climate change without altering the socio-ecological systems (Mapfumo et al. 2017). For example, replanting crops damaged by severe rainfall or flooding to sustain food productivity is a coping response. Incremental adaptation involves anticipatory approaches to accommodate climate change impacts based on slight adjustments to socio-ecological systems (Fedele et al. 2019). Examples of incremental adaptation include building walls to protect farmland against flooding, irrigation practices against drought, or other alternative approaches to providing nutrients to plants during unfavourable climate conditions.
conditions. In the face of increasing risks of climate change, coping strategies and incremental adaptation may be inappropriate in the long term, thereby demanding for transformative adaptation that addresses the root cause of vulnerability (Giacomo et al. 2019). Transformative adaptation is a strategy to build resilience in the long term by shifting systems (socio-economic and ecological) from unsustainable or undesirable trajectories to a just and sustainable path (Abubakar and Aina 2019; Walter et al. 2019). For example, in the case of flooding transformative adaption practice will involve relocating a farm area from the vulnerable low-lying flood plain. The general characteristics of transformative adaptation are path-shifting, restructuring, innovative, multiscale, systemwide, and persistent (Giacomo et al. 2019).

Transformative adaptation is often “path-shifting” because it changes the trajectory of a socio-ecological system to a more sustainable path (Giacomo et al. 2019). It involves identifying the root cause of the vulnerability and removing the cause or exposure (Abubakar and Dano 2020). Urban centres, for example, get increasingly congested by the years as many people are migrating from rural areas in search of a better livelihood. This migration results in increased industrial activities and fossil fuel burning, in addition to the loss of biodiversity, more pressures on infrastructures, and increased consumption, thus aggravating climate change due to increasing anthropogenic GHG emissions (Hasan et al., 2020). A radical shift in urban economy from fossil-fuel intensive activities to a more sustainable and ecological friendly activities like agriculture is a plausible transformative adaptation strategy to climate change (Chowdhury et al., 2020). Though concerns arise regarding the contribution of some agricultural activities such as bush clearing to GHGs emissions, there is growing evidence that urban farming is a viable approach to climate change adaptation and mitigation, if properly managed (De Zeeuw et al. 2011; Lwasa et al. 2015). Urban agriculture increases biodiversity and urban greening supports carbon sequestration and reduces Urban Heat Island (UHI) if it replaces open land and impervious surfaces (Lwasa et al. 2015). In addition, urban agriculture supports livelihood, enhances food security, and reduces poverty, thereby building the capacity of urban dwellers to adapt to and manage climate impacts (Lwasa et al. 2015; Fedele et al. 2019). The restructuring function of transformative adaptation is evinced by its ability to cause a change in fundamental properties, functions, or interactions within the socio-ecological systems (Fazey et al. 2018). For example, the development of new land use plans that restrict the creation of structures with high imperviousness surfaces. Transformative adaptation is also “innovative” since it often changes systems to new states that have not previously existed, leveraging new knowledge, policies, or technologies (Giacomo et al. 2019). These innovations include applying computer-assisted decision support system in farm management to simulate weather scenarios and provide timely information to farmers to change from monocropping to agroforestry. Further, transformative adaptation is “multi-scale” considering its far-reaching impacts across multiple scales (Giacomo et al. 2019). For example, the introducing agriculture to cities will improve the economy, sustain food security, and tackle climate change through carbon sequestration and reducing heat Islands. Despite its merits, some factors hinder the implementation of transformative adaptation, including low socio-political support, high cost of investments, and the long time required to successfully implement it (Kuntz and Gomes 2012). The need to involve multiple stakeholders, private sectors, and governments of varying interests may also delay or impede transformative adaptation.
3. Digitalization in agriculture

In this fourth industrial revolution era, advancements in information and communication technologies (ICT), including machine vision, automation, blockchain, IA, Internet of Things (IoT), and big data analytics, are breaking innovation boundaries and creating intriguing solutions. These cross-cutting digital solutions could not have been imagined some years back in almost all sectors, including business, finance, medicine, engineering, and agriculture. With the ubiquity of Internet-enabled mobile devices, timely access to scientific and technology-based information will enable farmers to optimize their resources, become competitive, and raise their income (Bronson, 2019; Nazarpour et al. 2011; Klerkx et al. 2019). Various ICT applications help meet farmers’ information needs, including “timely dissemination of agricultural information through online information services, education and training, monitoring, and consultation. Farmers’ access to agricultural information has also improved through databases established by the government and farmers’ organizations. Digitalization equally facilitates interaction among researchers, extension workers, and farmers. Further, it enables question-and-answer services where experts respond to queries on specialized subjects for greater efficiency in delivering services for overall agricultural development. These features can provide up-to-date information about subjects useful to farmers, such as, packages of production techniques/practices, management skills, market information, weather forecasting, agricultural statistics, policy and programs” (Nazarpour et al. 2011).

Great opportunities for digitization and automation of agricultural production processes exist with the rapid fall in the cost and increased efficiency and computational power of electronic systems like autonomic robotic systems, wireless networked IoT devices, and the advances in AI and machine learning (Grieve et al. 2019; Molotkova et al. 2020). With machine vision, there is advancement in understanding, modelling and crop mapping by hyperspectral remote sensing using ground-based, truck-mounted, airborne, and spaceborne sensors (Shamshiri et al., 2018; Thenkabail et al. 2011). Also, innovative technology solutions such as satellite tracking and aeromonitoring can support large scale digital farming, strengthen adaptation to climate risks, enhance disaster preparedness and aid effective planning and management of agriculture practices in urban Africa. This optimism stems from the effective utilization of digitalization for similar purposes outside the continent (Abubakar and Dano 2020).

Further, smart technologies that incorporate AI could reduce agricultural losses, forecast productivity, enhance agricultural production and support strategic decision making (Nazarpour et al. 2011; Cavazza et al. 2018; Grieve et al. 2019). For example, detecting plant diseases using naked eyes takes several days, after which application of pesticide might be ineffective. The conventional method of treating crops is pesticide application throughout the farmland. In contrast, digital technologies (e.g. small autonomous aerial or ground robotics and unmanned aerial vehicles) could fast-track timely detection of diseased crops in large farmland for prompt treatment (Grieve et al. 2019). With smart technologies, infected, unhealthy, or underdeveloped crops could be precisely isolated and treated. Equally important is the use of collated time series data and location patterns of infections as input in AI & machine learning technologies to process useful knowledge and predict future outcomes based on experience (Grieve et al. 2019). Also, AI can
integrate many seasonally fixed data such as soils, microbiomes, field locations, plant genetics with the variable ones like weather, fertilizers, crop protection chemistries, machinery operation to advice on the best farm management practices. Thus, it is pertinent to explore similar potentials of digital farming in Africa, which is the aim of the present study.

### 3.1. Digital urban farming

Urban farming entails cultivating, processing, and distributing food within or around urban locations, thereby enabling the provision of fresh food and strengthening cities’ resilience to climate change (FAO 2020). Minimal environmental impact, flexibility, and sustainability are major characteristics of urban farming methods such as rooftop, vertical, and indoor farming. Although digitalization is currently prevalent in non-urban agriculture (Knierim et al. 2019; Kullu et al. 2020), urban farming also benefits from digitalization. For example, recent sensor technology supports remote evaluation of environmental conditions for optimal control environment agriculture (CEA), while IoT can facilitate automation of the farming process (Charania and Li 2020; Li et al. 2020). Moreover, the rapid shrinkage of arable land in rural areas, exacerbated by the expansion of urban territory and change in rural labour to non-agricultural industries (Li et al. 2020), accelerates the shift from rural farming to urban farming. Based on the global trend, urban farming is expected to grow in the future, ensuring food security in cities and creating appealing clean-tech jobs for many new immigrants. Therefore, it is imperative to explore digital urban farming alongside the digitalization of rural farming. The next section details the application of digitalization in farming in different locations outside SSA.

### 4. Global perspectives on the applications of digitalization in farming

The emerging digital technologies and innovative solutions in the form of computer-assisted decision support systems (DSS) and simulation models strengthen agricultural resilience to climate risks and aid effective planning and management of farm practices. Examples of such systems are cropping simulator (CropSyst), AgroDSS, and Agricultural Production Systems Simulator (APSIMS). CropSyst is one of the earliest simulation models for analysing the effect of climate, soils, and management on cropping systems’ productivity and the environment (Stöckle et al. 2003). Its development started in the early 1990s and evolved into a suite of programs that include the CropSyst, a weather generator (ClimGen); GIS cooperator program (ArcCS), a watershed model (CropSyst Watershed); and several miscellaneous utility programs (Stöckle et al. 2003; Rupnik et al. 2019). The APSIM was developed by Queensland’s Agricultural Production Systems Research Unit in Australia to capture the interactions between soil water and nutrient dynamics, crop growth, climate and farmer management (Gaydon et al. 2017; Holzworth et al. 2018). The AgroDSS is a cloud-based DSS that enables the farmers to utilize several AI tools in a simplified interface for various purposes like predictions from simulated scenarios, structural detections and outputs the results to users in simple language (Rupnik et al. 2019). AgroClimate, an initiative of Southeast Climate Consortium (SECC), is another internet-based decision support and learning platform that shares agrometeorological information with farm managers to build agricultural vulnerability and mitigate
production risk to climate change (AgroClimate 2015). Several other crop growth simulation systems of varying capabilities, such as AquaCrop by FAO, SALTMED, and SWAP, have also been developed (Hassanli et al. 2016; Foster et al. 2017; Rupnik et al. 2019).

Some computer systems for dairy farm practices have also been developed. Baudracco et al. (2012) developed an animal simulation model, named e-Cow that predicts herbage intake, milk yield, and live weight change in dairy cows. Plà et al. (2004) and Pomar and Pomar (2005), in separate development, created a system for early identification of sows having low prolificacy performance in commercial pig farms (Rupnik et al. 2019). Allore et al. (1995) developed a system called MAST that determines weaknesses and problems of a mastitis control strategy by pinpointing problem areas, highlighting the scope of the mastitis problem, providing reference values for comparison, offering potential solutions to problem areas, and monitoring changes in the control strategy to systematically manage mastitis disease (Rupnik et al. 2019).

Table 1 presents case studies of digital farming from a global perspective. For example, a survey found 295 DSS and tools available to UK farmers, with about 46% of farmers using at least one of such tools for better productivity and environmental output (Rose et al. 2016). Some states in the USA, such as Nebraska, Alabama, Florida, Georgia, North and South Carolina, utilize Aquacrop systems for agricultural planning and generating local climatic data. In Nebraska, for example, Aquacrop systems are used for simulating maize crop yields under varying irrigation, nutrients, and soil scenarios (Sandhu and Irmak 2019). Aquacrop has also been successfully implemented in New Delhi, India (Abedinpour et al. 2012), and northern Serbia (Stricevic et al. 2011).

In developed countries, the adoption of digital farming has been associated with access to technological tools, large-scale farming, and the cultivation of cereal crops (Klerkx et al. 2019), which are generally lacking in developing countries, particularly in SSA. In Jiangsu Province, China, outstanding progress has been made in crop growth modelling, geographic information and DSS for crop management, automated monitoring of crop conditions, and precision control of production management (Xu et al., 2019). In Australia, the low penetration of digital agriculture has been attributed to shortage and high cost of ICT infrastructure and data, and low digital literacy among older farmers. Also, ownership of farm data and privacy concerns are the institutional issues undermining digital farming (Cho, 2018).

5. Methodology

This paper adopts a two-pronged approach. Firstly, it comprehensively describes key concepts of digital farming within urbanization, climate change, and sustainable perspective. Secondly, it uses a desk study approach to provide an in-depth literature review. A desk study was adopted to assess the current trend and prospects of digitalization to enhance agricultural practices in SSA. Secondary documents were analysed to examine the best way to achieve sustainable agriculture, enhance food security and availability in line with the UN’s sustainable development goals (SDGs) II (UN 2020). The desk study involves three iterative steps (Figure 1): the problem overview, literature sourcing, and synthesizing and discussing the findings. This approach has been employed in earlier studies ((Leal Filho et al. 2019) Abubakar and Aina 2019).
| Location          | Technology                                      | Benefits                                                                                   | Challenges                                                                                     |
|-------------------|------------------------------------------------|---------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------|
| Tacheng, Xinjiang, China | AGRAS MG-1 drone                               | • Cover up to 10 acres of farmland in one hour.                                               | • Drones faceairspeed and endurance limitations which lower the total area a single flight can cover. |
|                   |                                                | • Spray more than 3,295 acres of tomato farm in 20 days, a cost-saving of USD 275.19 per acre. | • It takes several flights, battery replacement and logistics to cover a 1 km² in-flight inspection (Trendov et al. 2019). |
|                   |                                                | • Spray 26 acres of cotton farmland in 4.5 hours, causing farmers to get USD 244.62 profit.     |                                                                                                |
|                   |                                                | • Captures videos and images that accurately show the development stages of crops and identify under-developed areas and areas in need of fertilizer (Shaft et al. 2019). |                                                                                                |
|                   |                                                | • Reduce pesticide use by 50%, water use by nearly 90%, and material and labour costs by 70% (Trendov et al. 2019). |                                                                                                |
| Epirus, Arta Plain, Greece | Internet-based Irrigation Management System (IRMA_SYS) | • Provide intelligence about irrigation system                                              | • Lack of sufficient technologies and essential infrastructures such as access to networks and basic technology needed to sustain the IRMA_SYS and related systems (Ojha et al., 2016; Trendov et al. 2019). |
| Florida, USA      | Robotic system                                 | • Collecting on-farm data to manage operations and increase yields.                         | • Lack of affordability and access to robotic systems as well as a technical aid for farmers (Hajjaj & Sahari, 2016; Trendov et al. 2019). |
|                   |                                                | • Pesticides and fertilizers application and weeding, which reduce the need for herbicides.    | • Lack of appropriate wireless network infrastructure to operate agricultural robots (Amer et al., 2015). |
| Santa Rosa de Cabal, Columbia | Wireless sensors network provided by Libelium technology | • Harvesting, packing, and transporting farm products such as strawberries.                  |                                                                                                |
|                   |                                                | • Calculating, mapping, and enhancing water use in irrigation (Trendov et al. 2019).          |                                                                                                |
| Minnipa, South Australia | VRT application automated system               | • General farm supervision.                                                                 | • Implementing technology is expensive as it requires machineries and equipment which are capital-intensive (Trendov et al. 2019) |
|                   |                                                | • Promote sustainable crop production.                                                      | • The wireless sensors network nodes are error-prone, which as a result affects the overall performance of the network (Younis et al., 2014) |
|                   |                                                | • Promote environmental sustainability.                                                     | • Network failures in harsh climatic conditions (Misra et al., 2014).                           |
|                   |                                                | • Sustainable management of organic waste.                                                   | • Lack of infrastructure.                                                                       |
|                   |                                                | • Trace and monitor crops conditions.                                                       | • Lack of access to loans.                                                                      |
|                   |                                                | • Provide safety of the farm products. (Enterprise IoT Insights, 2017)                      | • Lack of adequate skills and knowledge.                                                        |
|                   |                                                | • Irrigation scheduling                                                                      |                                                                                                |
|                   |                                                | • Increases yield and reduce workload                                                        |                                                                                                |
|                   |                                                | • Reduce the use of fertilizers and pesticides                                               |                                                                                                |
|                   |                                                | • Reduce risk by identifying poor and good yield areas.                                     |                                                                                                |
|                   |                                                | • Lower greenhouse gases emissions by reducing water and energy use (Zhao et al., 2018).    |                                                                                                |
The problem overview focused on the main objective of this study, which is to evaluate the potentials of digitalization to accelerate sustainable farming in Africa. Academic literature was searched and downloaded from of Google Scholar, Scopus, and Web of Science repositories to have a broad overview and reliable information. Other government sources such as the UN, IPCC, and FAO are also utilized for this study. Based on the literature search, six case studies across SSA were evaluated to examine the trend and prospects of digital farming. The selection of the case studies was based on the main theme of this paper which entails an assessment of future urbanization in SSA and likely risks to agriculture in the region. Specifically, the following criteria that have the potential to impact sustainable agricultural practices in SSA were considered:

(a) Digitalization
- Benefits of digitalization in farming
- Roles of digitalization in strengthening adaptation to climate risks, enhancing disaster preparedness, and aiding the effective planning and management of agricultural practices
(b) Challenges to digitalization in farming
- Challenges of implementing digital farming to boost food security.
- Ways of overcoming the identified challenges
(c) Characterization
- Regions applying the digitalization tools for agricultural sustainability
- Digitalization tools and concepts that are effective in farming

The literature search was based on the following Boolean operations: [digitalization OR digitization OR digital transformation] AND [agriculture OR farming OR urban farming OR digital farming] AND [climate change OR global warming] AND [benefits OR importance OR merits] AND [challenges OR issues OR problems] AND [Africa OR West Africa]. This method is adopted from similar studies ((Balogun et al. 2020). Finally, this study recommends more effective ways of implementing digitalization concepts to enhance food security and job creation in SSA.

6. Findings from the case studies in Africa

Digitization stimulates innovation for more improved and sustainable food systems while conserving natural resources and biodiversity. In Africa, however, the digitalization of agriculture is only recently gaining ground and is largely using mobile phone platforms (Tsan et al., 2019). Table 2 presents some exemplary case studies of digital farming in Africa, including the technologies used, their benefits (e.g. how the technologies support adaptation to climate change) and challenges. For example, Farmforce is a cloud-based mobile program launched in Kenya in 2012 to manage farming schemes of smallholder farmers. Leveraging advancements in mobile technology, Farmforce is deployed to improve market access and profitability for small-scale farmers by providing timely information on crop availability to buyers and facilitating a smooth delivery process. It also provides real-time online information through dashboards to monitor cropping activities and manage risks on farms (Farmforce, n.d; Loukos et al. 2019). The application has been employed in simulating
crop yield and water productivity of soya beans in Ile-Ife Nigeria (Adeboye et al. 2019). Farmforce’s digital innovativeness and versatility in catering to a broad spectrum of agribusiness needs can create scalable and commercially viable solutions.

In South Africa, FruitLook is a web-based technology that improves irrigation agriculture and water use efficiency through precise monitoring and managing crop production and water use. Such resources that support efficient water use are crucial to adaptation to climate change impacts in Africa. In a study of the adaptation strategies of small scale farmers during the 2015–18 drought in the Western Cape, South Africa (Fanadzo et al. 2021) concluded that lack of resources hampered the adaptation strategies of the affected farmers.

FruitLook also highlights crucial growth parameters to farmers weekly, helping farmers monitor crop growth and defects, and understand the impacts of climate change on-farm productivity. Multiple functionalities such as providing a snapshot of the Leaf Area Index (LAI) and quantitative information on Vegetation Index (NDVI) and Biomass production [kg/ha] make it suitable for smart rural and urban farming. Its Analysis tab also supports systematic time-series assessment of crop stress under varying climatic conditions.

In Tanzania, Zimbabwe, and Mozambique, Chameleon soil moisture sensor and FullStop wetting front detector are being used by irrigation farmers for monitoring the levels of water, nitrate, and salt in the soil. Efficient and effective water supply management with shrewd water administration crucial to Africa’s poverty alleviation and sustainable agriculture agenda (Stirzaker et al. 2017). But this is threatened by drought induced by climate change, which exacerbates water scarcity. Chameleon sensors and Fullstop detectors were deployed to record and plot weekly water, nitrate, and salt readings to generate pertinent colour codes using real-world case studies. The different colour patterns convey vital information on problems related to the measured parameters, prompting the farmers to take necessary action to minimize farm production risks. The ability of the Chameleon sensors to accurately assess water conditions on sites can help farmers make better farm management decisions, thereby saving water and coping with water scarcity which is projected to deteriorate with climate change. The Fullstop detectors also detect Nitrate leaching caused by excessive

Figure 1. Methodology flow chart.
irrigation, and the farmers on the surveyed sites responded by reducing irrigation, thereby optimizing water use on the farm. An interesting outcome from one of the case studies is the realization that visual examination of soil might not convey accurate information about its water stress level since soil can look dry on the surface despite the availability of sufficient water beneath the surface (Stirzaker et al. 2017). Thus, a novelty of the devices is remotely providing soil water availability information without physical extraction of soil.

In Uganda, the Grameen Foundation launched a mobile phone application called Farmers’ Friend that offers agricultural advice and targeted weather forecasts to local farmers. Utilizing weather reports obtained from the Department of Meteorology (DOM) and technical farming details sourced from Busoga Rural Open-Source Development Initiative (BROSDI), Farmers’ Friend’s SMS-based database offers rapid information for managing risks posed by crops diseases and regional weather forecasts (Grameen Foundation 2021). Forecasting extreme weather events is a common adaptation strategy to help communities cope with the devastating impacts of climate change (Balogun et al. 2020). However, communicating the weather information to end-users for prompt action could be challenging. Hence, Farmers’ Friend’s affordability ensures rural farmers in Uganda can access weather forecast information to support timely farm management decision making, minimize climate change impacts and promote sustainable farming. As a result of the pilot project’s success, there are plans to scale the application nationally across Uganda.

AgroClimate is another climate-smart agricultural management system in Mozambique. It leverages the strong influence of the El Niño-Southern Oscillation (ENSO) phenomenon to predict weather patterns based on the ENSO phase, provide climate information and statistics for each ENSO phase, and indicate favourable dates to sow tomato fruits based on ENSO information. The website utilizes geospatial data from the National Oceanic and Atmospheric Administration (NOAA) and other datasets from pertinent organizations (AgroClimate 2021).

Several digitization technologies are under development. For example, Oliveira-Jr et al. (2020) propose an IoT-based sensing platform that delivers information on soil and nearby environmental conditions such as pH, moisture, texture, colour, temperature, and light for improving yield via crop and soil management. In Kenya, Gichamba et al. (2016) developed a prototype mobile application in agriculture to receive experts’ advice on various farming operations.

7. Discussion and recommendations

Globally the advent of ICT and high computing power has transformed urban farming from tedious to continuously automated operations, thanks to ubiquitous connectivity, knowledge-based systems, DSS, big data sensors, IoT, and AI for mining information on more effective ways of food production (Bronson, 2019; Cambra Baseca et al., 2019; Shamshiri et al., 2018). These technologies have enormous potentials to facilitate large-scale digital farming to provide livelihoods to the rapidly growing urban populations in Africa amidst the continually shrinking urban land while reducing the negative environmental impacts of agricultural activities (Abubakar 2021). They also support adaptation to climate change as a major challenge to sustainable agriculture in Africa. As seen in the popular definition of Kates et al. (2012), transformative adaptation is underpinned by the scale or intensity of the proposed solution, innovativeness of the solution and the potential to transform places and/
| Location                  | Climate Change impacts                                                                 | Digital Technology                  | Benefits of digitalization                                                                                       | Challenges to digitalization                                                                 |
|---------------------------|----------------------------------------------------------------------------------------|------------------------------------|-----------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------|
| Nairobi, Kenya            | Drought, floods, heat stress, and disease, irregular precipitation variation,           | Farmforce: a cloud-based mobile    | • Access to real-time farming information from everywhere via mobile.                                          | • Shortage of mobile-friendly and locally appropriate digital content (Torero, 2013).       |
|                           | and increase in temperature/warming (Kamau and Mwaura 2013; Kogo et al. 2021)          | program                            | • Accurate farmland mapping to automatically calculate its size, the correct input needed (e.g. fertilizer),    | • Poor mobile infrastructure resulting in poor network signals, poor connectivity, and       |
|                           |                                                                                        |                                    | and damaged crops.                                                                                             | poor electricity supply                                                                      |
|                           |                                                                                        |                                    | • Real-time notification of the application of farm input or implementing recommended practices                | • Affordability problems as most mobile apps belong to a particular research project       |
|                           |                                                                                        |                                    | • Recording, monitoring, and identifying field staff and their routine activities.                             | (Trendov et al. 2019).                                                                      |
| Tare, Rwanda              | Temperature rise, drought, water quality and quantity, landslides increase flood and   | FAO-based mobile App               | • Timely information about crops, climatic change, rainfall distribution, livestock, and plant/animal diseases. | • Lack of internet affordability                                                               |
|                           | erosion, increase in new diseases and pests (Beuel et al. 2016; Gaspard et al. 2019)  |                                    | • Recommend types of crops to grow based on the existing climatic conditions.                                  | • Lack of good internet speed (Chair and De Lannoy, 2018).                                  |
| Oyo State, Nigeria        | Irregular rainfall intensity and pattern, pest and disease outbreak, flood and         | Farmforce cloud-based mobile       | • Access to market to sell farm products. (Ingabire et al., 2017).                                           | • Lack of adequate mobile infrastructure (Torero, 2013).                                     |
|                           | erosion, food shortage, reduction in farm yield (Akinbile et al. 2018; Tella and       | program                            | • Clear tracking information about visiting schedules of field officers providing agronomic training.            | • Expensive internet and the company’s customized mobile apps                                |
|                           | Balogun 2020)                                                                          |                                    | • Automated recording and printing of farm input/output details such as weights.                                 | • Dearth of mobile-welcoming and suitable digital content (Torero, 2013).                   |
| Western Cape, South      | Drought, warming, food security, water resources (Otto et al. 2018; Ziervogel et al.  | FruitLook Technology              | • Automatic calculations of expenditure required to complete crop cultivation.                                 | • Slow internet speed and inadequate mobile network infrastructure                           |
| Africa                    | 2014)                                                                                 |                                    | • Digital records of farmers’ crops and loan information to tackle the problems of defaulting (Farmforce).       | • Absence of native language content (Chair and De Lannoy, 2018)                             |
|                           |                                                                                        |                                    | • Provides real-time data on plants growth, water use efficiency, and nitrogen level                           | • Less viable for small-scale farmers                                                      |
|                           |                                                                                        |                                    | • It provides actual and deficits of evapotranspiration information.                                          | • Farmers experience limited consultations during the design processes (Aguera et al., 2020).|
|                           |                                                                                        |                                    | • It provides data on biomass production, leaf area index, and vegetation index.                              |                                                                                             |
|                           |                                                                                        |                                    | • It increases the quality and quantity of farm products (Fanadzo et al. 2021).                              |                                                                                             |
Table 2. (Continued).

| Location       | Climate Change Impacts                               | Digital Technology                  | Benefits of digitalization                                      | Challenges to digitalization                                    |
|----------------|------------------------------------------------------|-------------------------------------|-----------------------------------------------------------------|-----------------------------------------------------------------|
| Iringa, Tanzania | Pests and diseases outbreak, flood, reduction in precipitation amount, drought (Kassian et al. 2016) | Chameleon Sensor and FullStop detector | • Management of fertilizer and soil nutrients                     | • Expensive and short supply of the devices (Fanadzo et al. 2021). |
|                |                                                      |                                     | • Reduced water consumption and labour force                      |                                                                  |
|                |                                                      |                                     | • Increases crop yield (Fanadzo et al. 2021).                     |                                                                  |
|                |                                                      |                                     | • Search for farming guidelines via text message database        | • High smartphone and Internet costs (Andres and Woodard, 2013). |
|                |                                                      |                                     | • Real-time information on crops, livestock, disease, and pest control, crops planting, harvesting and storage guidelines, and weather forecasts (Torero, 2013). | • Poor internet speed and low e-literacy (Torero, 2013). |
| Kampala, Uganda | Increased temperature, decreased precipitation, rise in exposure to flooding, drought (Markandya et al. 2015; Sridharan et al. 2019) | Farmer’s Friend Mobile App | • Weather forecast                                                | • Lack of historical climate and weather data                   |
|                |                                                      |                                     | • Climate summaries and statistics                                | • Sustained funding (AgroClimate 2021)                           |
|                |                                                      |                                     | • optimal planting dates (AgroClimate 2021)                       |                                                                  |

or shift locations. The innovative use of digital technologies to communicate timely information on weather risks and seasonal variations (Table 2) can minimize risks, improve adaptation and boost the sustainability of rural and urban farming.

African farmers are just beginning to embrace digital farming, considered the 4th agricultural revolution where smart services such as autonomous systems and AI can radically transform all aspects of on-farm and off-farm agricultural processes. However, the existing efforts towards increased adoption of digital farming are nascent and faced with several challenges. Table 2 indicates that the challenges to adopting digital farming in Africa include unaffordable digital technologies, mobile phones, and data, especially among small-scale farmers, and lack of ICT awareness, digital skills, and literacy (Oliveira-Jr, et al., 2020). There is also the challenge of inadequate internet and cellphone infrastructure resulting in poor network signals, low internet speed and intermittent connectivity, and poor electricity supply (Trendov et al. 2019). Other challenges are the apprehension that digitization could lead to a drop in the unskilled workforce, narrow features and coverage of the technology, and language diversity among rural farmers. Thus, widespread adoption of digitization in Africa and elsewhere is only possible when the technologies are affordable, easy to use, meet farmers’ needs, and feasible for small sizes of urban land parcels, common in most African countries. In Nigeria, for instance, households owned an average of 0.5 hectares of land in 2016 (Abubakar 2021). However, plans to scale digitization applications for broader coverage and output in the future as being proposed with Kenya’s Farmforce and Uganda’s Farmers’ Friend’s digital applications are encouraging.

Overcoming the limited adoption of digital farming in Africa and other developing countries requires a multi-faceted approach. First, farmers should be trained to acquire ICT skills for using the technologies and know which ones will satisfy their needs. Formal schools, cooperatives, and organizations are avenues for improving the farmers’
proficiencies in basic ICT literacy and skills. The ICT is an enabler of digital farming because it supports farmers in their operations and decision-making (Aubert et al., 2012). Second, there is the need to improve digital infrastructure to address the issues of the absence of or unstable internet connectivity and fluctuating speeds. Developing digital infrastructures and mobile technologies at the grassroots is imperative for effective data transfer and deployment of digital solutions and innovations (Cho, 2018). Third, low-cost access to digital infrastructure and technologies is a prerequisite for the successful use of ICT in farming, especially for low-income farmers. Fostering competition among ICT providers can substantially lower access costs. Similarly, state intervention via subsidized access to data and digital technologies would ensure that farmers are not isolated from the ICT revolution key to digital urban farming (Cecchini and Scott, 2003). Addressing digital farming challenges in Africa is a key to the effective implementation of digitalization concepts that recorded many successes in developed countries (Abedinpour et al. 2012).

Analysis of Table 2 indicates that most digitalization applications in Africa are domiciled in rural areas amongst smallholder farmers. This discovery agrees with an observation that urban farming is less visible globally and is only beginning to trend recently (Kullu et al. 2020). One of the trending urban farming systems that African cities should consider is digital greenhouse farming. In several developed countries such as the Netherlands, France, and Italy, this smart farming within a controlled environment is a practice that succeeded in meeting the increasing food demand exacerbated by the loss of arable land due to urban expansion, pollution, and erosion (Ayaz et al., 2019). Sensors and ICT are increasingly being used to support growing crops indoors, which are less affected by the external environment (Shamshiri et al., 2018) and less susceptible to climate change impacts. Through greenhouse farming, crops limited to certain regions of the world or climatic conditions can be grown in any place and at any time of the year. Through wireless sensors, digitization and DSS facilitate greenhouse farming in cities by improving the monitoring precision of environmental and climatic parameters, including temperature and ventilation systems (Ayaz et al., 2019). Also, wireless imaging sensors and GPS devices can allow the autonomous collection of data inside greenhouses and mapping environmental variables (Shamshiri et al., 2018). Thus, greenhouse farming can help attain food security while creating several clean-tech jobs in African cities.

In some urban centres, hydroponic farming as an irrigation system of cultivating plants without soil, is a solution to space and water scarcity challenges, especially in large cities. It is very important in meeting the food security for urban dwellers because it is highly suitable for growing many crops in any city as balanced nutrients are dissolved in water used in growing the crops. Recycled municipal wastewater is increasingly being used for low-cost irrigation in urban areas (Mu’azu et al., 2020). Recent advances in digitization and scientific innovations in plant nutrition and growth make hydroponic farming more efficient and more attractive in urban areas. Hydroponics can help conserve our fast-declining arable land, forest resources, and natural animal habitats while improving urban sustainability (Ayaz et al., 2019).

Another urban farming technology that is crucial to overcoming the challenges of food shortages and shrinking arable land is vertical farming. Because plants are stacked in a more controlled environment, this method substantially reduce resource consumption by increasing production spaces. Unlike traditional farming practices, only a fraction of ground surface is used in vertical farming (Ayaz et al., 2019). In Mirai (Japan), lettuce yield through vertical farming is twice that produced through traditional farming methods and consumes 40% less
energy and up to 99% less water consumption. In Newark (USA), vertical farming recorded up to 390 times higher yields while utilizing 95% less water than traditional farming methods (Ayaz et al., 2019). When vertical farming is combined with hydroponics, a site measuring 100 square metres can yield the crop equivalent to 1 acre of the traditional farm, with about 95% less water and fertilizer utilization and negligible use of pesticides or herbicides (Ayaz et al., 2019). The minimal water consumption feature can boost adaptation to climate-induced drought. Indeed, digital urban farming, especially vertical, greenhouse, and hydroponic farming systems have vast potentials to provide livelihoods for the rapidly growing urban populations in Africa while fostering food security and environmental sustainability.

In cities such as Dubai, Shanghai, and Medellín (Colombia), vertical farms, wetlands, and home gardens are used to grow a variety of food. Other cities utilize old factories and abandoned warehouses to grow crops alongside existing residential and commercial structures (Benke and Tomkins, 2017). In Singapore, vertical farming up to 120 towers produce two tons of vegetable daily, providing the nation with greater food sufficiency and exports worth USD10,000 per tower (Benke and Tomkins, 2017). Apart from yearly cultivation of healthy crops, less influence of drought, pests, and floods, vertical farming ensures high yields up to six times compared to conventional agriculture and slashes the cost of transporting food to cities, lower water consumption and recycle treated wastewater (Kalantari et al., 2017).

8. Conclusion

This study examines the implementation of digitalization in urban farming in Africa by assessing various case studies, taking into consideration the following parameters: (a) climate change impacts on urban farming in the continent; b) the extent of adopting digitalization in urban farming; and (c) challenges to digitized urban farming. Based on literature search focused on keywords such as climate change, digitalization, GIS, IoT, and urban farming, this study highlights the limited adoption of digitalization in urban farming by most African cities. However, it was discovered that the introduction of digitalization to farming in African cities could improve food security for the ever-growing African population and aid adaptive urbanization in several ways. First, digital urban farming can increase food production by aiding effective planning, decisions, and management practice. Second, digitization can help reduce production loss by building agricultural resilience and reducing farm vulnerability to climate risks.

Urban farming offers transformative adaptations to climate change for developing cities. This adaptation strategy has the potential to shift the urban economy from industry-dominated to agriculture-based services. This will reduce activities that result in GHG emissions while supporting food availability for the growing number of urban residents. Digital urban farming, especially through home gardens, rooftops, vertical and hydroponic farms, and greenhouses can support mitigation efforts against climate change by encouraging the creation of low-carbon jobs. It can also reduce carbon emissions from transporting food and enhance the “sinks” that store the heat-trapping greenhouse gasses. The carbon sequestration role of urban farming can reduce the urban heat Island effect, improve air quality by reducing pollution, and create a more sustainable urban environment. Despite its merits, sustainable digital urban farming is threatened by different risks. Limited digital
infrastructure and energy poverty were identified in most of the studied cities. The lack of a clear and common understanding of digital urban farming concepts and the data required to develop mobile-friendly and locally appropriate digital content was also highlighted. The absence of digital content in the native language of the farmers impedes effective communication and citizen engagement.

Similarly, the affordability of mobile infrastructure, apps, and internet services make digital farming less feasible for small-scale farmers, underscoring the digital divide and inequality that pose significant risks to digital urban farming in Africa. Another issue is low e-literacy, fuelled by continuous use of conventional data collection techniques and reluctance to digitalize farming practices. This problem is exacerbated by the social inequality and cultural barriers in many African communities where women, who constitute a significant portion of the agriculture industry, have limited access to education and a low level of digital literacy. Nonetheless, opportunities to overcome these challenges and mainstream digitalization in Africa’s urban farming space exist. Widespread and consistent training to help farmers acquire ICT skills are essential, just as the need to improve digital infrastructure to address the absence of unstable internet connectivity and fluctuating speeds. In the future, it is essential to implement government policies and strategies to subsidize access to data and digital technologies to ensure that farmers are not isolated from the ICT revolution key to digital urban farming. Also, further studies are required to explore a broader range of digital innovation in Africa’s agriculture sector and undertake a comprehensive assessment of future and emerging risks.

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Data availability statement

Data sharing does not apply to this article as no primary data were collected or analyzed in this study.

ORCID

Abdul-Lateef Balogun http://orcid.org/0000-0002-0418-3487
Ismaila Rimi Abubakar http://orcid.org/0000-0002-7994-2302
Umar Lawal Dano http://orcid.org/0000-0002-6786-5223
Abdulwaheed Tella http://orcid.org/0000-0002-4380-3343
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