Discover Environment

Review

Leveraging information and communication technologies for sustainable agriculture and environmental protection among smallholder farmers in tropical Africa

Patrick Ngulube[1]

Received: 2 October 2024 / Accepted: 16 January 2025
Published online: 23 January 2025

Abstract
Using a qualitative approach, this study examines the role of information and communication technologies (ICTs) in promoting sustainable agriculture and environmental protection among smallholder farmers in tropical Africa. It emphasises how tools such as community radios, mobile phones, satellite systems, and artificial intelligence provide crucial market data, weather forecasts, and agricultural practices. The research highlights the need for equitable access to ICT solutions to narrow the digital divide and foster sustainable development. Among these technologies, community radio stations and mobile phones are identified as the most accessible and affordable options for many farmers, and they can effectively spread knowledge about sustainable practices. While advanced technologies like the Internet of Things (IoT), drones, and artificial intelligence have the potential to enhance agricultural productivity and environmental conservation, their adoption in tropical Africa is often hindered by challenges related to infrastructure and literacy. This study demonstrates the role of ICTs in enhancing agricultural productivity and environmental sustainability among smallholder farmers in tropical Africa. It emphasises the need for equitable access to digital tools and strong policy frameworks to tackle infrastructure and literacy challenges, which are essential for closing the digital divide. The study underscores the need for policy formulation to include these strategies and for professionals to adopt them to enhance agricultural productivity and environmental sustainability among smallholder farmers in tropical Africa.

Keywords Digital innovations · ICT integration · Environmental preservation · Food security · Natural resources · Precision farming · Resource management

1 Introduction and background

Agriculture and environmental sustainability are inextricably linked [1, 2]. Protecting the environment and promoting sustainable agriculture are significant challenges facing tropical Africa. Biodiversity is declining due to population expansion, extensive agriculture, urbanisation, infrastructural development, and the illegal wildlife trade [3]. Decreasing rainfall affects agricultural output, exacerbating food security issues [4]. Land degradation, deforestation, and ecosystem loss are further aggravated by extreme climate change vulnerability [5]. The increasing water scarcity negatively affects ecosystems, livelihoods, and agriculture [6]. To address these issues, quick action is needed to protect Africa's environment and promote sustainable practices, especially among smallholder farmers.

✉ Patrick Ngulube, ngulup@unisa.ac.za | [1]School of Interdisciplinary Research and Postgraduate Studies, University of South Africa, Pretoria, South Africa.

Smallholder farmers, who own 80% of all farms in Africa, play a crucial role in ensuring food security and advancing several United Nations Sustainable Development Goals (SDGs) [2, 7–10]. Studies reveal that 70% of the food consumed worldwide is grown by smallholder farmers [11], and agriculture is a vital industry since it provides a living for over 70% of Africa's people [12]. These small-scale farms are usually located in underdeveloped, rural areas and operated by low-income, food-insecure families with limited access to markets and services [13].

Sustainable development involves meeting present needs "without compromising the ability of future generations to meet their own needs" ([14], p. 43). SDGs emphasise balancing present demands and long-term sustainability [15]. Smallholder farmers hold the key to addressing challenges posed by climate change, poverty, inequality, and environmental deterioration through sustainable practices. However, they face numerous challenges, including budgetary limitations, in their quest for sustainable practices and environmental protection [9].

Research demonstrates that information and communication technologies (ICTs) such as radio, television, mobile phones (smartphones), personal computers, laptops, tablets, computer networks, wired and wireless networks, cloud computing, satellite systems, blockchain, and artificial intelligence (AI) (i.e., chatbots, virtual assistants, and machine learning (ML) systems) [16, 17] have a potential to drive sustainable agriculture and environmental protection in tropical Africa and provide chances for international integration [16, 18]. Electronic data, knowledge, and information on agriculture and environmental protection can be recorded, stored, used, distributed, and accessed with the help of these technologies [16, 17, 19, 20]. ICTs utilise voice, short message service (SMS), web portals, and call centres to provide farmers with information and advisory services [21]. By enabling farmers to access market data, weather forecasts, and new technologies, ICTs can help increase productivity, enhance living standards, and support agricultural extension services [22, 23].

Optimising these technologies can lead to sustainable agriculture and environmental conservation in line with the SDGs, which aim to end extreme poverty, achieve zero hunger, provide affordable and clean energy, reduce inequality, and protect the planet by 2030 [10]. ICTs can reduce carbon emissions five times greater than the sector's total emissions [24, 25]. This potential addresses global environmental issues like climate change, significantly reducing greenhouse gas (GHG) emissions and promoting sustainability. Although ICTs account for around 2% of annual global GHG emissions, the benefits of ICT adoption for humanity seem to exceed the disadvantages [26].

When incorporated into extensive development strategies, goals, and objectives, some ICTs may significantly improve people's livelihoods through agriculture and environmental management [27]. Access to these technologies can speed up social, economic, and political growth in marginalised, impoverished, and vulnerable areas, such as most parts of tropical Africa [16]. There is ample evidence supporting the benefits of ICT for environmentally friendly practices and sustainable agriculture. Environmental sustainability [28] and agricultural productivity [12, 29] are increasing by adopting ICT technologies.

Several ICT tools can boost agricultural output and promote resource sustainability and efficiency [20, 30]. They provide data and information on early warning systems, new varieties, production optimisation, and managing diseases and pests [20]. The effective and efficient capturing, storing, retrieving, and disseminating of market information, market intelligence, and agricultural extension rely on ICTs [31]. The Internet of Things (IoT) can connect various devices and sensors to collect and analyse data [32], improving efficiency and reducing pollution; mobile apps can provide farmers with real-time information and advice on soil and water management; drones can be used to monitor fields, assess soil conditions, and manage water resources; AI and ML can help with data analysis and make informed decisions about managing soil and water [30, 33]. By enhancing monitoring systems, cutting down on resource usage, and encouraging environmental activism, ICTs can also help to manage the environment [34].

However, infrastructure gaps underscored by the digital divide, unsuitable policies, and insufficient user skills are likely to reduce access to these technologies by many people in the developing countries of tropical Africa due to their socio-economic status, location, ethnicity, or race [16, 35]. While ICTs have the potential to make agriculture more intelligent and sustainable [28], digital technologies predominantly target major businesses rather than women and small-scale farmers, especially in developing countries, and they cannot address the digital agricultural needs of smallholder farmers because the digital ecosystems are underdeveloped and infrequently used [9]. For instance, smallholder farmers, particularly those in developing nations like Tanzania, face challenges with the accessibility and viability of digital services [36].

Despite the rise of disruptive and intelligent technologies, a discussion on the importance of low-tech ICTs for sustainable agriculture and protecting the environment in tropical Africa is still pertinent. It reinforces the need to prioritise them above other technologies for sustainable development among smallholder farmers. Rather than merely using technology for its own sake, the focus should be on specific agricultural needs like crop management and market information. Besides, not all cutting-edge technology is superior, and combining old and new technologies can sometimes yield more significant results [37].

The study is positioned by referencing more recent studies and an extensive literature examination. It contributes to the expanding study body by critically integrating ICT for environmental and agricultural sustainability. To comprehend how optimising ICT resources can contribute to sustainable agriculture and environmental protection in tropical Africa, this article explores the use of ICTs for sustainable agriculture, environmental progress through ICTs, and the challenges and opportunities of optimising ICTs for driving sustainable agriculture and environmental protection in tropical Africa. Additionally, it offers a conceptual framework that could be utilised for further research to gain a more comprehensive understanding of the topic.

The following questions helped to shape the study.

- What ICT tools and technologies can help support sustainable agriculture and environmental protection among smallholder farmers in tropical Africa?
- Can ICTs support what agricultural practices are needed for smallholder farmers in tropical Africa?
- How can ICTs promote environmental protection for smallholder farmers in tropical Africa?
- What challenges do smallholder farmers encounter in utilising ITCs to promote sustainable agriculture and environmental protection in tropical Africa?
- What opportunities do ICTs offer smallholder farmers in tropical Africa to implement sustainable agriculture and protect the environment?
- Who are the key stakeholders in using ICTs to support sustainable agriculture and protect the environment among smallholder farmers in tropical Africa?

2 Methodology

This study utilised a qualitative research design that focused on conducting a comprehensive literature review and content analysis to investigate the role of ICTs in promoting sustainable agriculture and environmental protection among smallholder farmers in tropical Africa. Content analysis is a systematic method that follows clearly defined rules and procedures, ensuring consistency and replicability [38, 39]. This methodological rigour enhances the reliability and validity of the findings. Additionally, content analysis is cost-effective and efficient, allowing researchers to quickly process large volumes of information. Unlike other methods that may focus solely on qualitative or quantitative aspects, content analysis, like mixed methods research, offers a holistic view, making it an indispensable tool for modern research [38, 39].

Several studies demonstrate the effectiveness of qualitative approaches and content analysis in researching ICTs, sustainable agriculture, and environmental protection. For instance, one study employed this method to conduct a computer-assisted bibliographic search and examined empirical studies [40]. Another study effectively used content analysis to identify critical practices, challenges, and future strategies for digital agriculture [41]. Furthermore, content analysis was instrumental in uncovering digital systems' challenges, benefits, and adoption rates in smallholder contexts [9, 36].

This approach allowed for a thorough understanding of existing knowledge, theories, and practices related to the research topic. The literature review formed the foundation of this research, involving a detailed examination of existing studies, reports, and theoretical frameworks. In line with previous studies [36, 40, 41], the review process included identifying relevant academic journals, books, conference papers, and reports from reputable organisations such as the United Nations, the World Bank, and various agricultural research institutions. Databases like Google Scholar, JSTOR, Scopus, Web of Science, and PubMed were extensively searched using keywords combined with Boolean operators to ensure comprehensive coverage of terms and concepts.

The structure of the search query was the following. ("Information and Communication Technologies" AND "Sustainable Agriculture" AND "Tropical Africa") OR ("ICT" AND "Environmental Protection" AND "Smallholder Farmers") OR ("Digital Tools" OR "Mobile Technology" AND "Agriculture" AND "Africa")OR ("Sustainable Farming" AND "ICT" AND "Developing Countries") OR ("Precision Agriculture" AND "Information Technology" AND "Sub-Saharan Africa") OR ("Climate-Smart Agriculture" AND "ICT" AND "Smallholder Farmers") OR ("Agricultural Innovation" AND "Digital Solutions" AND "Tropical Regions") OR ("Environmental Sustainability" AND "ICT" AND "Agricultural Practices") OR ("E-Agriculture" AND "Sustainable Development" AND "Africa") OR ("Mobile Applications" AND "Farm Management" AND "Tropical Agriculture")“Mobile Applications” AND “Farm Management” AND “Tropical Agriculture”).

The literature search resulted in 1 989 documents; however, only 29 of them were analysed in detail. The literature search results were uploaded, and the retrieved articles were imported into the Zotero reference manager for screening

[42]. Subsequently, the articles were transferred to CADIMA version 2.2.4.2, an open-access tool designed to facilitate the conduct and documentation of systematic reviews and systematic maps [43, 44]. CADIMA automatically identified and removed duplicate records, ensuring that the dataset was clean and manageable. CADIMA also standardises the documentation and reporting process by providing detailed documentation of each step in the review process, ensuring methodological rigour and consistency [44, 45].

The tool also allowed for screening titles and abstracts based on predefined inclusion and exclusion criteria. For records marked as relevant, CADIMA facilitated the full-text screening process. The inclusion and exclusion criteria were established to filter the retrieved records, ensuring that the literature review was comprehensive, relevant, and of high quality. The studies targeted in this review focused on tropical Africa or regions within tropical Africa, with research populations consisting of smallholder farmers. The selected studies needed to cover topics related to ICT, sustainable agriculture, environmental protection, or a combination of these areas. Only recent studies published within the last 10 years were considered to ensure that the information was current. Additionally, only studies published in English were included. Peer-reviewed journal articles, conference papers, and reports from reputable organisations like the UN and Farm Radio International were considered. Only studies providing relevant insights into the use of ICT for sustainable agriculture or environmental protection were included in the review.

Content analysis was employed to systematically analyse the data collected from the literature review [46]. This method involved coding and categorising textual information to identify patterns, themes, and relationships. The steps involved in the content analysis included data coding, categorisation, thematic analysis, and validation, which involved the triangulation of data from multiple sources and perspectives to confirm the consistency and accuracy of the results and to conduct the review with integrity and respect for intellectual property [47]. Data codes were derived from the research questions that guided the study. Coding resulted in the code coding frame, which outlined and structured the data as illustrated in Appendix I. The coding frame made data manageable and categorisation possible.

To enhance the reliability and validity of the screening process, CADIMA's feature for allocating records to multiple reviewers was utilised, enabling independent and parallel assessments. The independent review was conducted by a postdoctoral fellow familiar with ICTs for development. Intercoder reliability was achieved by adhering to the coding frame in Appendix 1. That ensured that all the coders understood the coding categories consistently [48]. The coders also regularly assessed and discussed the coding discrepancies to resolve differences and improve agreement [49]. Examples of coding are provided in Appendix II.

Significant data segments were identified and labelled to create categories [50]. The [ICT Tools and Technologies] category included all references to various ICTs used in agriculture and environmental protection. The [Agricultural Practices] category covered different sustainable agricultural practices and methods mentioned in the documents. The [Environmental Protection] category addressed aspects related to conservation and protection efforts facilitated by these technologies. The [Challenges] category identified the barriers and obstacles to adopting and implementing ICTs for sustainable agriculture and environmental protection. The [Opportunities] category highlighted the potential benefits and advantages of using ICTs in agricultural and environmental management. Lastly, the [Stakeholders] category outlines the parties involved in this process, including farmers, government bodies, NGOs, and private sector entities.

Initially, categories were reviewed to find commonalities and relationships [51]. The process involved grouping related categories to form broader themes that capture the essence of the data [52]. Thematic analysis identified and analysed the themes within data, but the themes were not transformed into measurable variables as in some content analysis studies [53, 54] the aim was to get an overview of the optimisation of ICTs in sustainable agriculture and environmental protection rather than quantifying their impact. The findings are presented in the subsequent sections.

3 Leveraging ICTs for sustainable agriculture

The data confirms that ICTs have the power to transform agriculture into sustainability. ICTs can help farmers better access information and services that enhance farming techniques, production, and livelihoods. With ICTs, smallholder farmers can boost agricultural output using less money and resources and spending less time on farm management, marketing, logistics, and quality control, enhancing productivity and sustainability [55]. However, adopting practices like precision agriculture or smart agriculture, which leverages technologies such as the Internet of Things (IoT), sensors, drones, and data analytics to achieve sustainable resource management and contribute to environmental conservation, is still elusive to many smallholder farmers in tropical Africa due to a variety of reasons and the digital divide [32, 56, 57].

Community radio stations and mobile phones are the mainly accessible and affordable ICTs to many farmers in tropical Africa [1, 56, 58].

3.1 Community radio stations for sustainable agriculture

According to the United Nations, radio is still one of the most comprehensive, inclusive, trusted, and widely available media for information dissemination worldwide, especially in Africa, where literacy levels are relatively low [59, 60]. Although the cost of ICT services is declining, over half of the world's population still does not use the Internet [61], and these figures have not increased significantly [62]. Historical data shows that 75 per cent of households can access a radio [22, 63]. In 2012, at least 75% of households in developing countries had access to a radio [64]. Community radio in sub-Saharan Africa grew by nearly 1400% between 2000 and 2006 [65]. In rural tropical Africa, mobile phones are paired with devices like cell phones to develop a two-way communication medium where listeners may voice their opinions, ask questions, and get feedback over the airwaves [66]. The community radio stations strive to improve radio's interaction and efficacy by fusing it with contemporary technologies such as smartphones and computers. Hybrid models combining radio and contemporary technologies assist in overcoming the difficulties caused by digital literacy [1].

Using mobile phone technology, community radio stations throughout tropical Africa are pivotal in providing knowledge on best practices for sustainable agriculture and empowering women and youth. Through the YenKasa Africa programme, Farm Radio International partnered with the Government of Canada, the Food and Agricultural Organisation of the United Nations (FAO) and the World Association of Community Radio Broadcasters (AMARC) to produce radio programmes and mobile phone polling systems with radio stations in Ghana [67]. This project aimed to empower small-scale farmers in Ghana by sharing best practices, weather reports, and lessons learned via cooperative participation in the spirit of YenKasa, a local Akan word used in Ghana that means "Let's talk."

Utume FM in central and northern Tanzania collaborated with local NGOs such as Changamoto Youth Development Organization (CYDO) and Youth Peacemakers (YPM) to promote environmentally sustainable agriculture practices that benefit the community economically and socially. Utume FM's strategy of providing tree seedlings improved women's involvement in Uliza, (i. e. ask in KiSwahili), polls by 30% using the Uliza interactive system developed by Hangar Radio and ICT Innovation Lab in Arusha [68]. The system combined radio, mobile phones, and interactive voice response to engage listeners [63, 69]. Aiming to provide high-quality interactive radio programming on environmentally sustainable agriculture practices to at least 2 million small-scale farmers in Tanzania's northern and central regions, this programme is a part of the Interactive Radio for Ecologically Sustainable Agricultural Practices (IRESAP) which involved multiple radio stations and local organisations in Tanzania [70].

Twelve radio stations in Uganda were home to e-extension platforms that reached 1.5 million rural farmers [63, 71]. This ensured that 70% of small-scale farmers in a nation where just 5% of the 80% of families involved in agriculture received advice from extension workers in 2019 were given knowledge on implementing sustainable agricultural techniques. Ugandan farmers were given access to knowledge about circular and regenerative agriculture using Interactive Radio for Farmers in collaboration with the Ugandan Ministry of Agriculture. This allowed them to ask questions and share their experiences. Farmers acquired various skills, such as cultivating sugarcane for cow fodder and employing organic techniques to keep fungus off coffee trees [72]. By extending the community radio system to provide price information, weather alerts, and extension information, the rice industry in Mali became more competitive. Information on research, weather, climate, and best agricultural practices was provided via Kenya's Farmer Voice Radio Project [73].

Ugandan women also utilised community radio stations to enhance their farming methods [74]. The Women of Uganda Network (WOUGNET) expanded women farmers' access to agricultural information and knowledge through various multi-channelled ICT-enabled platforms, including web-based platforms and radio talk shows. In addition to establishing a multifaceted information hub to give access to ICTs and agrarian information, partnerships were started with community radios to broadcast weekly agricultural programmes in local languages. This project underscores the need to consider and address gender issues when utilising digital tools in rural and agrarian communities. In rural and farming areas, considerate use of ICTs can ensure gender equality, empower women, and reduce poverty. Women are marginalised in the field of digitalization for agriculture (D4Ag). The Technical Centre for Agricultural and Rural Cooperation (CTA)/Dalberg report on D4Ag in Africa painted the picture in the following words:

In sub-Saharan Africa, where 40–50% of smallholder farmers are women, only 25% are registered users of D4Ag solutions. Companies that explicitly target female farmers and make this an important measure of their success tend to do better. Overall, the data suggest that companies are not sufficiently prioritising gender as part of their product design, marketing and user engagement efforts ([75], p. 21).

These examples demonstrate that community radio stations can be utilised to empower farmers and promote sustainable and eco-friendly farming methods. Consequently, ministries of agriculture and the private sector in tropical Africa prioritise and place a high value on community radio stations as they work to offer all farmers consistent, affordable extension and advisory services. Such approaches will lead to sustainable agriculture that will eradicate poverty and zero hunger in many rural areas, which aligns with the SDGs.

Even though ICTs may be limited, social networks can play a significant role in supporting them. Tropical Africa's social networks and/or systems can facilitate knowledge exchange [22]. A message from a reliable source can be swiftly distributed to clan members, members of solidarity associations, and other community members after being received from a few people with radios or cell phones. Social networks, emphasizing the value of in-person contacts and collaborative knowledge creation, provide knowledge-intensive support systems essential for sustainable agriculture [75].

3.2 ICTs and digitalization of agriculture

Integrating IoT solutions in agriculture has given rise to intelligent agriculture, also known as precision agriculture, which uses drones and sensors to collect data, improving efficiency and decision-making in farming [76, 77]. The billions of remote electronic gadgets wirelessly linked to complex networks to create intelligent architecture are called the IoT [78]. Real-time weather, crop health, and soil condition monitoring made possible by IoT have completely changed farming. Farmers get information on air quality, soil characteristics, and other vital aspects using in-situ sensors. Precision agriculture uses aerial imagery from drones fitted with sensors and cameras. Soil sensors, remote sensing, AI, and big data can enhance crop output and quality while minimizing resource consumption and environmental impact [79].

Despite the availability of the digital infrastructure as described in the preceding paragraph and the transformational potential of digital technologies, sophisticated devices like crop sensing tools, the Internet of Things (IoT), and AI cannot be effective among many smallholder farmers in tropical Africa. The understanding of the value of digital agriculture systems is limited [9], and complete digitalization is still a ways off [80]. Access to digital technologies remains unaffordable and inappropriate for some local conditions in tropical Africa [8, 37, 58, 81, 82]. For instance, studies in Malawi and Ghana have shown that most farmers favour digitization and think it could improve agriculture. However, actual usage and involvement are minimal [8, 58]. There is also limited use of high-tech digital technologies due to knowledge and the intrinsic qualities of smallholder farmers and technology [83]. Moreover, NGO activities, as opposed to individual ones, are the primary drivers of farmers' use of digital services in many countries in tropical Africa [58]. Low literacy rates, a lack of digital skills, and restricted access to resources frequently cause participation to decline as soon NGOs change their focus.

While some farmers may not have access to modern technologies, the Nigerian federal government adopted the strategy of providing extension workers with ICT like digital farm mapping, soil type identification, meteorology, and agricultural records. The idea behind this approach is that the extension workers can provide farmers with information they would have acquired through the traditional training and visit (T&V) extension approach [82]. ICT-enabled agriculture has been implemented in Rwanda using a "digital green projector" to increase agricultural productivity by disseminating agricultural knowledge and technical information [84, 85]. Rwanda used the same model as Nigeria, whereby the government trained facilitators and agronomists who, in turn, trained rural farmers. The model is worth emulating in other tropical countries where access to new technologies is limited so that the farmers can access information from state-of-the-art technology. However, the model does not entirely address the access and availability of these technologies to smallholder farmers.

3.3 Mobile applications for agricultural competitiveness and sustainability

ICT tools can improve market access, lower transaction costs, reduce intermediary dependency, and boost agricultural development programmes' production in tropical Africa. Supply chain management, commodities exchanges, farm extension services, financial services, and market information systems are a few examples of mobile apps that can achieve sustainability in agriculture. Mobile apps provide real-time weather forecasts, market prices, and agricultural advice. Simple text messages can deliver critical information to farmers.

Mobile apps assist smallholder farmers to conduct financial transactions more easily, quickly, and safely thanks to M-PESA in Kenya and Tanzania, mobile money in Ghana, Mozambique, Uganda (MOBIS), Zambia, and WIZZIT in South Africa. To respond to quality standard requirements, track, manage, pay, and reward small producers, and record movements along the value chain, Dunavant Cotton utilised mobile applications in Zambia and the dairy industry in Kenya [73]. Messages about markets, weather, and farming advice are sent to users via Farmerline's mobile app in their local languages in Ghana [86]. Through weekly SMS texts, farmers in Sudan received irrigation information from the eLEAF irrigation advice service, which used satellite, meteorological, and field-level data. Farmers received information about soil moisture, evapotranspiration, nitrogen levels, crop development, and when to irrigate their crops. The information assisted farmers in keeping an eye on their crops and making informed choices [87].

Using SMS, newsletters, and radio, N'kalô, an agricultural market information system that serves West Africa, collects, analyses, and disseminates data on cashews and other crops in the region. It also gives farmers, dealers, and other value chain participants access to the most recent market information. That helped to dramatically raise the price of cashew nuts, which had fallen to an unsustainable level, particularly in 2008 [88]. Since 2011, M-Farm has enabled Kenyan farmers to access buyers, exporters, and large-scale retailers via mobile phones [89]. By lessening the impact of middlemen, M-Farm empowered farmers and made the agricultural ecosystem more effective and transparent. Due to M-Farm's integration with Mpesa, Kenya's mobile money system, unbanked farmers can effortlessly handle their income [90].

In Nigeria, 20 million farmers benefitted from the government Growth Enhancement Support (GES) scheme, designed to deliver government-subsidised farm inputs directly to farmers using a global system for mobile (GSM) phones. The e-wallet vouchers provided through the phones enabled farmers to purchase fertilisers, seeds and other agricultural inputs from agro-dealers at half the usual cost [37]. The system of subsidising farmers was discontinued in 1997 because corrupt officials were diverting the supplies to large-scale farmers or other profit-seeking individuals, leaving less than 10–15% of the supplies to the intended beneficiaries. The use of mobile technology reduced corruption and improved the delivery of agricultural inputs for rural farmers [91, 92]. With 90% of the fertilizer reaching the targeted farmers and the government saving a substantial amount of money, using ICTs increased transparency and cost-effectiveness [92].

Blockchain makes agricultural supply chains transparent and traceable. Blockchain is used by Agrikore in Nigeria, Zambia, Ghana, Zimbabwe, Tanzania, Uganda, Botswana, Mozambique, Malawi, and Liberia to track produce from farm to market, lowering fraud and boosting confidence [93]. More than 7 million farmers have benefited from Agrikore, a mobile blockchain-based smart contracting, digital payments, customer relationship management, and marketplace platform that has improved their access to the market and made it easier for them to sell their products to a broad spectrum of consumers. Access to information, inputs, produce, and financial markets are all made possible for agriculture stakeholders (i.e., agro-dealers, governments, development partners, financial institutions, insurance companies, farmers, and community produce aggregators) by Agrikore [94]. With the help of a comprehensive system made up of business processes, technology, and operating models, Agrikore, sometimes referred to as an eWallet system, organises the players in agriculture in a way that makes it highly "de-risked and investable" on a big scale [93]. This is the first time a system ensuring contract "immutability, integrity, and transferability" within agriculture has been implemented in Africa [94].

In Rwanda, inadequate handling and unfavourable environmental conditions resulted in considerable postharvest losses before adopting ICTs [95]. Due to insufficient processing, drying, and crop harvest storage, postharvest losses could reach 22% [95]. By utilising the ThingSpeak platform, farmers can minimise losses and maintain the quality of their maize by using the global system for mobile (GSM) phones to send a brief message in the event of critical drying or storing environmental conditions under which the grains of maize are stored [95].

3.4 Satellite imagery and remote sensing

Agricultural management has used satellite data to estimate productivity, monitor crop health, and control irrigation [96]. Countries in tropical Africa leverage satellite data for land use mapping, crop monitoring, and disaster management. Using satellite data to support decision-making promotes sustainable land management and the best use of available resources.

Using satellite data, farmers in Sudan participating in the Gezira Irrigation Scheme have significantly enhanced crop yields, especially wheat, while increasing irrigation frequency and improving water use efficiency per irrigation [97]. Satellite images are used to measure the growth of crops (i.e., biomass production [BP], leaf area index [LAI], and normalized difference vegetation index [NDVI]), moisture (i.e., actual evapotranspiration, evaporation deficit, crop factor, and biomass water use efficiency) and minerals (nitrogen in upper leaf, and total plant nitrogen) [98]. After farm location mapping, the piece of land is linked with the mobile number to facilitate information delivery through SMS.

On the other hand, the Rwanda Smart Satellite Crop system helps with trend analysis and provides almost real-time crop production monitoring, which helps with managing Rwanda's agricultural industry [99]. It tracks crop development using the Normalised Difference Vegetation Index (NDVI), updated every ten days using data from Sentinel satellites. Vital information regarding crop health, growth, and environmental conditions is provided by monitoring [100].

In a nutshell, ICTs have the potential to significantly enhance sustainable agricultural practices among smallholder farmers in tropical Africa. Key ICT tools include community radios, mobile phones, satellite systems, and advanced technologies such as the Internet of Things (IoT), drones, and artificial intelligence (AI). Community radios and mobile phones are the most accessible and affordable options, effectively sharing knowledge on best practices, weather forecasts, and market data. These tools help improve productivity, reduce costs, and promote efficient resource use. However, constraints like infrastructure gaps, digital literacy, and affordability hinder the widespread adoption of advanced technologies. This section emphasises the importance of integrating both traditional and modern ICTs to overcome these challenges and promote sustainable development in agriculture.

3.5 Environmental advancements through ICTs

Many countries in tropical Africa are confronted with environmental issues stemming from human activity, such as the combustion of fossil fuels, oil spills, deforestation, and climate change. This partly explains why goal 7 of the *Agenda 2063* aims to achieve "environmentally sustainable and climate-resilient economies and communities" in Africa [101]. Environmental challenges in tropical Africa encompass air pollution, water quality, waste management, energy efficiency, climate change, and biodiversity loss [102]. Smallholder farmers are essential to ecological conservation [103–105]. To maintain food security and ecosystem resilience, smallholders create creative coping mechanisms for climatic variability [103, 104]. Smallholder farmers frequently grow various crops and stick to traditional agricultural methods to protect biodiversity and ecosystem services. Smallholder farmers support environmental sustainability and national food security by growing a variety of nutrient-dense foods [106]. They preserve water, increase soil fertility, and lessen soil erosion by utilising agroforestry, contour farming, and crop rotation [105–108]. To reduce chemical consumption and promote ecological balance, many smallholder farmers utilise natural techniques to control diseases and pests. Covering crops, mulching, and terracing all aid in preventing soil deterioration and enhancing soil health. Without knowledge sharing, preserving the environment and achieving sustainable development are complex tasks [109, 110].

Smallholder farmers promote collective environmental stewardship by sharing best practices and information [111]. ICTs can potentially assist smallholder farmers in mitigating environmental issues [110]. It has been aptly stated, "As humanity grapples with the consequences of unsustainable practices, the role of technology has emerged as a beacon of hope, offering innovative solutions to mitigate environmental degradation and promote long-term resilience" [57]. ICTs can contribute to the flow of information, data collection, and communication, making them potentially effective tools for environmental conservation and sustainable resource usage.

Sustainable development and environmental protection are complex without the flow of information [109]. Smallholder farmers can improve environmental sustainability and encourage the prudent use of natural resources by utilising ICTs. For instance, using satellite data facilitates monitoring many environmental activities, including deforestation, desertification, and changes in land use [96]. Furthermore, drones have the potential to revolutionize precision agriculture by enabling better soil mapping, pest monitoring, and yield optimization. These advancements could mitigate soil degradation, which affects 65% of Africa's agricultural land, and encourage sustainable practices leading to higher yields [112].

Although ICTs make it easier to monitor and manage natural resources, improving data gathering and analysis for the preservation of the environment, there is a need to consider the reality of smallholder farmers where simple devices like mobile phones, radios, and televisions still predominate due to low literacy, a lack of digital skills, and restricted access to resources [18]. Using simple technologies aligns with their modest indigenous and sustainable land management techniques, which have supported biodiversity preservation, reduction of greenhouse gas emissions, and ecosystem equilibrium [113].

However, there are opportunities to develop digital solutions tailored to smallholder farmers' specific needs and constraints to improve agricultural productivity and food security in Africa. Mobile phone technologies, for example, can be used in conjunction with community radio stations to gather and distribute information about responsible resource use and environmental preservation.

3.6 Community radio stations

A study showed that smallholder farmers relied on radio stations to get 54.7% of their primary sources of information on climate change [114]. In that light, non-governmental organisations such as the Technical Centre for Agricultural and

Rural Cooperation (CTA), Grameen Foundation, FHI 360 and Farm Radio International employ community radio stations to disseminate information on environmental protection [1, 11, 76]. With the help of mobile phone-based technologies coupled with community radio stations, FHI 360 created the Climate Change Adaptation and ICT (CHAI) programme in Uganda to distribute climate change information gathered from rural weather stations [115]. The programme had a significant impact, and it was awarded the e United Nations Framework Convention on Climate Change Momentum for Change Lighthouse Activities Award, which honours ground-breaking approaches to tackling climate change and more significant social, economic, and environmental issues.

Six sub-Saharan African nations use radio documentaries and podcasts to exchange climate change adaptation techniques [116]. In collaboration with the Government of Canada, Farm Radio International employs high-impact radio programming to identify, disseminate, and support locally generated nature-based solutions in Burkina Faso, Côte d'Ivoire, Ethiopia, Ghana, Uganda, and Zambia. The solutions are then amplified to a network of 3,500 broadcasters in 38 African countries to be replicated throughout the continent. Currently, 200 radio stations in Africa are telling the stories of rural people using natural solutions to cope with climate change and biodiversity. Gender equality is emphasised in the initiative, which seeks to change social conventions and give women's and youths' needs and contributions priority [Inclusive nature-based solutions: addressing climate change and biodiversity loss in rural Africa through high impact radio programs [117].

3.7 The future and the use of ICTs for environmental protection

In all regions, there has been a steady increase in the number of people using the Internet [118]. However, the use of the Internet by many smallholder farmers is limited by the business model of mobile communication technology operators and high costs. Most rural communication providers employ a "sparse coverage" approach, focusing on heavily populated areas and important rural highways that are not near where smallholder farmers work [85]. Generally, rural wireless networks often struggle to support hotspot data transmission due to slow speeds [85] and poor network connectivity [119].

While there is a noticeable difference in internet usage between regions, with North Africa and Southern Africa having significantly higher percentages of internet users than Central, East, and West Africa, there is hope that the growth of internet usage will enable smallholder farmers in tropical Africa to benefit from digital technologies that assist environmental protection [118]. Despite the expansion, there are still issues, such as the need for a more inclusive ICT policy and the low penetration of fixed telephone and internet services.

If there were the necessary infrastructure, tropical Africa would benefit from sensors, embedded devices, and analytics in environmental monitoring and improving its quality of life [120]. Some other ICTs that can help protect the environment if the infrastructure is available include satellite imaging, remote sensing, and data analytics [121]. Monitoring and restoring biodiversity can be supported by advanced techniques such as geographic information systems (GIS), artificial intelligence, and remote sensing. These techniques help to streamline the collection, analysis, and interpretation of large volumes of data, thereby optimising work processes [122]. ICT-enabled solutions can offer e-learning platforms, webinars, and virtual reality experiences to promote environmental education, awareness, and behaviour change [123–125].

ICTs can enhance smallholder farmers' monitoring and management of natural resources. This can help tackle environmental challenges in tropical Africa, including land degradation and climate change. Tools such as satellite imagery, remote sensing, drones, and mobile phones facilitate the monitoring and managing of natural resources, including deforestation, desertification, and land use changes. Community radio stations and mobile technology are crucial in disseminating climate change information and promoting sustainable practices. These resources enable smallholder farmers to adopt environmentally friendly methods, conserve biodiversity, and improve soil and water management. However, smallholders often lack access to modern technologies such as D4Ag solutions. Challenges such as limited internet access, high costs, and low digital literacy remain obstacles. This discussion highlights the importance of developing inclusive ICT policies and infrastructure to maximise the environmental benefits of ICTs and support sustainable development.

3.8 Challenges and opportunities for using ICTs for sustainable agriculture and environmental protection

Access to ICTs can lead to sustainable agriculture and environmental protection. ICTs can facilitate data processing, organising, and sharing, enabling smallholder farmers to stay current on agricultural and cutting-edge farming practices and environmental protection. However, the use of ICTs for sustainable farming and environmental protection is not without its difficulties. Prominent barriers include disparities in digital access, costs, infrastructure limitations, and legal gaps [125]. Sustainable farming and environmental protection prospects are restricted by the digital divide caused by unequal access to technology and the internet, particularly in tropical Africa. The acceptance and efficacy of D4Ag solutions are constrained by inadequate digital infrastructure (such as electricity and internet access) in rural areas [1].

An enabling environment that includes institutional, economic and social factors is required [126]. For farmers to benefit from the potential presented by ICTs, some institutional requirements must be met, such as having access to energy, a network and broadband. High-quality broadband is essential. Governments should invest in expanding broadband coverage to all rural communities, ensuring reliable and fast internet connectivity [127]. Collaborating with private sector entities to deploy and maintain ICT infrastructure can lower costs and increase access to ICTs by smallholder farmers. Erratic power supplies, fluctuating networks, high costs of ICT infrastructure, low incomes of rural farmers, lack of cohesive policies to enhance ICT development in rural areas, limited access to digital resources, and a lack of necessary skills to use the technologies are some of the problems faced by smallholder farmers in tropical Africa [82, 128, 129].

Farmers' use of ICTs may also be hampered by social and economic variables such as age, literacy levels, and availability of financing [126]. Furthermore, devices, conduits, and literacy enable smallholder farmers to overcome the digital divide, which prevents farmers from fully benefiting from the advantages provided by ICTs [130]. There is an apparent gender digital divide as women have limited access to many ICTs [131]. Ensuring equal access to ICT solutions in rural areas is essential for bridging the digital gap and promoting sustainable development. Inequitable access to ICTs leads to fragmented knowledge-sharing networks. Limited access to information, expertise, and resources inhibits collaboration, innovation, and sustainable development. Bridging these knowledge gaps is crucial for promoting collaboration, sharing best practices, and driving collective impact [1].

4 Conclusions

ICTs play a significant role in supporting sustainable agriculture and environmental protection. Action is needed to promote sustainable ICT adoption in tropical Africa. ICT services are not accessible and affordable for rural populations. That prevents many smallholder farmers from reaping the benefits offered by ICTs. Adoption of various technologies, including mobile networks, satellite-based solutions, and community networks, remains limited due to infrastructure challenges. Using traditional ICTs is crucial in sharing information and best practices among smallholder farmers. For instance, community radio stations and cell phones remain important communication channels for many smallholder farmers in tropical Africa. Additionally, social networks help bridge the gap for farmers lacking access to ICTs by providing a platform for collaboration and information exchange with those with access to ICTs.

Long-term environmental protection and sustainable agriculture cannot be driven solely by ICTs. They must be incorporated into more comprehensive plans designed to optimise their advantages for advancing agriculture and the environment. For ICTs to succeed, government funding and policy play a critical role. Merely investing in ICT is insufficient; extension services and education programmes that include local farmers are equally crucial. Digital literacy levels vary significantly among smallholder farmers, often creating a significant barrier to the effective use of ICT tools. The challenge is not only in understanding the basics of using devices but also in grasping the diverse requirements of various ICT solutions. Fostering digital literacy programmes can enhance their skills and confidence.

The methodology used in this article has apparent limitations. Using secondary data may introduce bias due to variations in quality and accuracy. The literature review may be limited by the availability of relevant studies, particularly in tropical Africa. Additionally, the researcher's subjective interpretation may influence the content analysis. However, the conceptual framework provides a basis for future research. The conceptual framework can be tested using field data to develop a robust theoretical framework for the optimum use of ICTs for sustainable agriculture and environmental protection.

4.1 Recommendations

Fostering an atmosphere conducive to ICT adoption and emphasising agricultural extension and training programmes, particularly for younger and older farmers, is recommended. To encourage the use of ICT and ensure long-term success, it is essential to have educational programmes and government support. Training and education can empower rural farmers to use ICTs effectively. Governments should invest in ICT infrastructure and create policies that promote the adoption of sustainable technologies in agriculture and environmental protection. This includes providing subsidies for technology adoption, offering training programmes for farmers and involving all the stakeholders in the provision of ICTS to support smallholder farmers in tropical Africa.

The policy frameworks must consider affordability for rural populations, relevance to their specific needs, and the unique local challenges and opportunities they face. Additionally, partnerships with the private sector are essential. Since a complete transition away from conventional technologies is impractical, investments should focus on developing capabilities and growing hybrid ICT models. These models integrate traditional ICTs with modern technologies inspired by successful community radio station initiatives. Building on existing ICTs can create sustainable solutions without starting from scratch. Moreover, it is critical to address data ownership and security concerns, particularly with the rise of new data governance systems.

Acknowledgements The author acknowledges the postdoctoral fellow who assisted with the coding and the anonymous reviewer who attended the College of Graduate Studies writing for publication retreat at the University of South Africa in July 2024.

Author contributions PN conceptualised the research, searched the databases, analysed the data and wrote the manuscript text.

Funding The current study received no funding.

Data availability No datasets were generated or analysed during the current study.

Code availability Not applicable.

Declarations

Competing interests The authors declare no competing interests.

Appendix I: Coding frame for analysing of data using content analysis

1. ICT Tools and Technologies (ICT)
   - Radio (RAD)
   - Mobile Phones (MOB)
   - Satellite Systems (SAT)
   - Artificial Intelligence (AI)
   - Internet of Things (IoT)
   - Drones (DRN)
   - Blockchain (BLK)
   - Mobile Applications (APP)

2. Agricultural Practices (AGP)
   - Sustainable Agriculture (SAG)
   - Precision Farming (PFM)
   - Climate-Smart Agriculture (CSA)
   - Organic Farming (ORG)
   - Agroforestry (AFR)

3. Environmental Protection (ENV)
   - Biodiversity Conservation (BDC)
   - Water Management (WAM)
   - Soil Health (SOH)

- o Deforestation Prevention (DFP)
- o Climate Change Mitigation (CCM)

4. Challenges (CHL)

- o Infrastructure Gaps (INF)
- o Digital Divide (DDV)
- o Literacy and Skills (LIT)
- o Cost and Affordability (CST)
- o Policy and Regulation (POL)

5. Opportunities (OPP)

- o Market Access (MKT)
- o Knowledge Sharing (KSH)
- o Resource Efficiency (REF)
- o Economic Viability (ECV)
- o Social Equity (SEQ)

6. Stakeholders (STK)

- o Smallholder Farmers (SHF)
- o Government Agencies (GOV)
- o Non-Governmental Organizations (NGO)
- o Private Sector (PRV)
- o Community Groups (COM)

Appendix II: Examples of Coding

- RAD: "Community radio stations throughout tropical Africa are pivotal in providing knowledge on best practices for sustainable agriculture."
- MOB: "Mobile phones are paired with devices like cell phones to develop a two-way communication medium."
- SAG: "Promoting environmentally sustainable agriculture practices that benefit the community economically and socially."
- BDC: "Smallholder farmers frequently grow various crops and stick to traditional agricultural methods to protect biodiversity and ecosystem services."
- INF: "Infrastructure gaps underscored by the digital divide, unsuitable policies, and insufficient user skills."
- MKT: "Mobile apps provide real-time weather forecasts, market prices, and agricultural advice."
- SHF: "Smallholder farmers, who own 80% of all farms in Africa, play a crucial role in ensuring food security."

References

1. Beanstalk AgTech. State of the digital agriculture sector. Harnessing the potential of digital for impact across agricultural value chains in low- and middle-income countries. 2023. https://www.beanstalkagtech.com/d4aglmic. Accessed 10 Jul 2024.
2. Giller KE, Delaune T, Silva JV, et al. Small farms and development in sub-Saharan Africa: farming for food, for income or for lack of better options? Food Security. 2021;13:1431–54. https://doi.org/10.1007/s12571-021-01209-0.
3. Cleanbuild Climate Action Innovation LTD/GTE. 5 Critical environmental challenges in Africa in 2024. 2024. https://climateaction.africa/5-environmental-challenges-africa-2024/. Accessed 7 Jul 2024.
4. Institute for New Economic Thinking. Perspectives on the challenges for sustainable development in Africa. 2024. https://www.ineteconomics.org/events/ysi-africa-convening-1/sustainability-perspectives-on-the-challenges-for-sustainable-development-in-africa. Accessed 7 Jul 2024.
5. United Nations Environmental Programme. Our work in Africa. 2024. https://www.unep.org/regions/africa/our-work-africa. Accessed 8 Jul 2024.

6. Economic Commission for Africa (ECA). New and emerging challenges in Africa summary report. 2011. https://sustainabledevelopment.un.org/index.php?page=view&type=400&nr=502&menu=1515. 2011. Accessed 8 Jul 2024.
7. African Union Development Agency (AUDA-NEPAD). Agriculture in Africa: transformation and outlook. 2022. https://www.tralac.org/images/docs/6460/agriculture-in-africa-transformation-and-outlook.pdf. Accessed 18 Jul 2024.
8. McCarthy C, Nyoni Y, Kachamba DJ, Banda LB, Moyo B, Chisambi C, Banfill J, Hoshino B. Can drones help smallholder farmers improve agriculture efficiencies and reduce food insecurity in Sub-Saharan Africa? Local perceptions from Malawi. Agriculture. 2023;13:1075. https://doi.org/10.3390/agriculture13051075.
9. Gumbi N, Gumbi L, Twinomurinzi H. Towards sustainable digital agriculture for smallholder farmers: a systematic literature review. Sustainability. 2023;15:12530. https://doi.org/10.3390/su151612530.
10. United Nations. 17 Sustainable Development Goals. 2015. https://sdgs.un.org/goals. Accessed 2 Jul 2024.
11. Grameen Foundation. Annual Report 2020. https://grameenfoundation.org/documents/GF_AnnualReport_FY2020_protected.pdf. Accessed 12 Jul 2024.
12. Ayim C, Kassahun A, Addison C, Tekinerdogan B. Adoption of ICT innovations in the agriculture sector in Africa: a review of the literature. Agric Food Secur. 2022;11:22. https://doi.org/10.1186/s40066-022-00364-7.
13. BASF. Smallholder empowerment. 2024. https://agriculture.basf.com/global/en/sustainable-agriculture/partnerships/smallholder-empowerment. Accessed 11 Aug 2024.
14. United Nations General Assembly. Report of the world commission on environment and development: our common future. United Nations General Assembly, Development and International Co-operation: Environment, Oslo, Norway. 1987.
15. International Institute for Sustainable Development. Sustainable Development. 2024. https://www.iisd.org/mission-and-goals/sustainable-development. Accessed on 10 Aug 2024.
16. Awati R. Definition: ICT4D (Information and Communications Technologies for Development). 1999–2024. https://www.techtarget.com/WhatIs/definition/ICT4D-Information-and-Communications-Technologies-for-Development. Accessed 2 Jul 2024.
17. UNESCO Institute for Statistics (UIS). Information and communication technologies (ICT). Guide to measuring information and communication technologies (ICT) in education. Montreal: UIS; 2009. https://unesdoc.unesco.org/ark:/48223/pf0000186547. Accessed 2 Jul 2024.
18. Abdulai A-R, Quarshie PT, Duncan E, Fraser E. Is agricultural digitization a reality among smallholder farmers in Africa? Unpacking farmers' lived realities of engagement with digital tools and services in rural Northern Ghana. Agric Food Secur. 2023;12:11. https://doi.org/10.1186/s40066-023-00416-6.
19. Thakur K, Pathan ASK, Ismat S. An overview of ICT technology advancement. In: Emerging ICT technologies and cybersecurity. Cham: Springer; 2023. https://doi.org/10.1007/978-3-031-27765-8_1.
20. Kishore MR, Thomas A, Kishore Kumar NK. Role of ICT in agriculture and environment. National Seminar on 'Contemporary Techniques in Environmental Research and Conservation (CTERC-2014). 2014. https://www.academia.edu/45164459/role_of_ict_in_agriculture_and_environment. Accessed 3 Jul 2024.
21. Nyirenda-Jere T. Unlocking the promise of ICTs for transforming agriculture in Africa. 2010. https://knowledge.cta.int/Dossiers/S-T-Policy/ICKM-MIS-ICT/ICT-for-transforming-research-for-agricultural-and-rural-development/Feature-articles/Unlocking-the-Promise-of-ICTs-for-Transforming-Agriculture-in-Africa.html. Accessed 13 Aug 2024.
22. Asenso-Okyere K, Mekonnen DA. The importance of ICTs in the provision of information for improving agricultural productivity and rural incomes in Africa. United Nations Development Programme Working Paper (WP 2012–015). 2012. https://www.undp.org/africa/publications/importance-icts-provision-information-improving-agricultural-productivity-and-rural-incomes-africa. Accessed 28 Jun 2024.
23. Domguia EN, Asongu S. ICT and agriculture in Sub-Saharan Africa: Effects and transmission channels, AGDI Working Paper, No. WP/22/007, African Governance and Development Institute (AGDI), Yaoundé. 2022. https://hdl.handle.net/10419/262075. Accessed 16 Aug 2024.
24. International Telecommunications Union. The broadband bridge: linking ICT with climate action for a low-carbon economy. ITU, Place des Nations. 2012. https://www.broadbandcommission.org/Documents/Climate/BD-bbcomm-climate.pdf. Accessed 5 Jul 2024.
25. UNFCCC. ICT sector helping to tackle climate change. 2016. https://unfccc.int/news/ict-sector-helping-to-tackle-climate-change. Accessed 5 Jul 2024
26. Friedrich R Ullrich S Hill K. Role of ICT in sustainable development and triple green win. 2023. https://www.bcg.com/publications/2023/role-of-ict-in-sustainable-development-triple-green-win. Accessed 5 Jul 2024.
27. Hamel, JY. ICT4D and the human development and capability approach: the potentials of information and communication technology. New York; 2010. https://hdr.undp.org/system/files/documents/hdrp201037.pdf. Accessed 2 Jul 2024.
28. Bilali H, Bottalico F, Ottomano Palmisano G, Capone R. Information and communication technologies for smart and sustainable agriculture. In 30th Scientific-Experts Conference of Agriculture and Food Industry: Answers for Forthcoming Challenges in Modern Agriculture. Springer International Publishing. 2020: 321–334.
29. Seat AS, Pather S. Adoption of ICT to support rural small-holder farmers: a systematic review. African Conference on Information Systems and Technology. 5. 2023; https://digitalcommons.kennesaw.edu/acist/2023/presentations/5.
30. Méndez-Zambrano PV, Tierra Pérez LP, Ureta Valdez RE, Flores Orozco ÁP. Technological innovations for agricultural production from an environmental perspective: a review. Sustainability. 2023;15:16100. https://doi.org/10.3390/su152216100.
31. Rohila AK, Yadav K, Ghanghas BS. Role of information and communication technology (ICT) in agriculture and extension. J Appl Nat Sci. 2017;9:1097–100. https://doi.org/10.31018/jans.v9i2.1328.
32. Chandler S. Agriculture IoT promotes sustainable practices. 2021. https://www.techtarget.com/iotagenda/feature/Agriculture-IoT-promotes-sustainable-practices. Accessed 2 Jul 2024.
33. Subeesh A, Mehta CR. Automation and digitization of agriculture using artificial intelligence and internet of things. Artif Intell Agric. 2021;5:278–91. https://doi.org/10.1016/j.aiia.2021.11.004.
34. Ugwuishiwu BO, Obi OF, Ugwuishiwu CH. Information and communication technologies: benefits and challenges to the environment. Int J Soft Comput Eng (IJSCE). 2013;6:96–100.

35. Abate GT, Abay KA, Chamberlin J, Kassim Y, Spielman DJ, Paul Jr Tabe-Ojong M. Digital tools and agricultural market transformation in Africa: Why are they not at scale yet, and what will it take to get there? Food Policy. 2023;116: 102439. https://doi.org/10.1016/j.foodpol.2023.102439.
36. Mushi GE, Di MarzoSerugendo G, Burgi P-Y. Digital technology and services for sustainable agriculture in Tanzania: a literature review. Sustainability. 2022;14:2415. https://doi.org/10.3390/su14042415.
37. International Bank for Reconstruction and Development. ICT in agriculture: connecting smallholders to knowledge, networks, and institutions (Updated Edition). Washington DC: World Bank Group; 2017. http://documents.worldbank.org/curated/en/455701468340165132/ICT-in-agriculture-connecting-smallholders-to-knowledge-networks-and-institutions. Accessed 7 Jul 2024.
38. Hassan M. Content analysis—methods, types and examples. https://researchmethod.net/content-analysis/. Accessed 12 Dec 2024.
39. Neuendorf KA. The content analysis guidebook. 2nd ed. Thousan Oaks: SAGE Publications; 2017.
40. Ribeiro MIB, Guarda T, Lopes IM, Fernandes AJG. Impact of ICT on the agricultural sector's sustainability: evidence based on practices. In: Gervasi O et al. Computational science and its applications—ICCSA 2023 workshops. ICCSA 2023. Lecture Notes in Computer Science; 14108. Springer, Cham. 2023. https://doi.org/10.1007/978-3-031-37117-2_8.
41. Yuan Y, Sun Y. Practices, challenges, and future of digital transformation in smallholder agriculture: insights from a literature review. Agriculture. 2024;14:2193. https://doi.org/10.3390/agriculture14122193.
42. Zotero 7 for Windows: Your personal research assistant. https://www.zotero.org/download/. Accessed 7 Jul 2024.
43. CADIMA. CADIMA is a free web tool. 2012–2024. https://www.cadima.info/. Accessed 12 Dec 2024.
44. Kohl C, Unger S, Haddaway N, Kecke S, Wilhelm R. CADIMA: An open-access online tool supporting the reporting and conduct of systematic reviews and systematic maps. 2017. https://abstracts.cochrane.org/2017-cape-town-global-evidence-summit/. Accessed 12 Dec 2024.
45. Kohl C, McIntosh EJ, Unger S, Haddaway NR, Kecke S, Schiemann J, et al. Online tools supporting the conduct and reporting of systematic reviews and systematic maps: a case study on CADIMA and review of existing tools. Environ Evid. 2018;7:1–17. https://doi.org/10.1186/s13750-018-0115-5.
46. Krippendorff K. Content analysis: an introduction to its methodology. 5th ed. Thousand Oaks: Sage; 2018.
47. Graneheim UH, Lindgren BM, Lundman B. Methodological challenges in qualitative content analysis: a discussion paper. Nurse Educ Today. 2017;56:29–34.
48. O'Connor C, Joffe H. Intercoder reliability in qualitative research: Debates and practical guidelines. Int J Qual Methods. 2020;19:1–13. https://doi.org/10.1177/1609406919899220.
49. Dovetail. Intercoder reliability and how it influences data accuracy. 2023. https://dovetailapp.com/research/intercoder-reliability. Accessed 13 Dec 2024.
50. Saldaña J. The coding manual for qualitative researchers (4th edition). Thousand Oaks: Sage; 2021.
51. Clarke V, Braun V. Thematic analysis. J Posit Psychol. 2016;12:297–8. https://doi.org/10.1080/17439760.2016.1262613.
52. Nowell LS, Norris JM, White DE, Moules NJ. Thematic analysis: Striving to meet the trustworthiness criteria. Int J Qual Methods. 2017. https://doi.org/10.1177/1609406917733847.
53. Vaismoradi M, Turunen H, Bondas T. Content analysis and thematic analysis: implications for conducting a qualitative descriptive study. Nurs Health Sci. 2013;15:398–405. https://doi.org/10.1111/nhs.12048.
54. Hecker, J Kalpokas N. The ultimate guide to qualitative research—Part 2: Handling qualitative data. https://atlasti.com/guides/qualitative-research-guide-part-2. Accessed 12 Dec 2024.
55. Sørensen CAG, Kateris D, Bochtis D. ICT Innovations and smart farming. In: Salampasis M, Bournaris T, editors. Information and communication technologies in modern agricultural development. HAICTA 2017, Communications in Computer and Information Science. Springer, Cham. 2019; 953: 1–19; https://doi.org/10.1007/978-3-030-12998-9_1.
56. ISO. Smart farming: the transformative potential of data-driven agriculture. https://www.iso.org/smart-farming/smart-farming-data-driven. Accessed 4 Jul 2024.
57. Datafloq. The role of technology in sustainable development and environmental conservation. 2024. https://datafloq.com/read/the-role-of-technology-in-sustainable-development-and-environmental-conservation/. Accessed 4 Jul 2024.
58. Abdulai AR, TettehQuarshie P, Duncan E, Fraser E. Is agricultural digitization a reality among smallholder farmers in Africa? Unpacking farmers' lived realities of engagement with digital tools and services in rural Northern Ghana. Agric Food Secur. 2023;12:11. https://doi.org/10.1186/s40066-023-00416-6.
59. Insideradio.com. Radio found to be trustworthy among fans of all media. 2021. https://www.insideradio.com/free/research-radio-found-to-be-trustworthy-among-fans-of-all-media/article_c4c08260-69e6-11eb-b696-1f45f8104061.html#. Accessed 7 Jul 2024.
60. United Nations (UN). Radio: the universal medium that leaves no one behind. 2022. https://news.un.org/en/story/2022/02/1111882 Accessed 7 Jul 2024.
61. International Telecommunications Union (ITU). ITU releases 2016 ICT figures. 2016. https://www.itu.int/en/mediacentre/pages/2016-PR30.aspx. Accessed 7 Jul 2024.
62. International Telecommunications Union (ITU). World Telecommunication/ICT Indicators Database 2023 (27th edition/December 2023). 2024. https://www.itu.int/en/ITU-D/Statistics/Pages/publications/wtid.aspx. Accessed 7 Jul 2024.
63. Hudson HE, Leclair M, Pelletier B, Sulliva B. Using radio and interactive ICTs to improve food security among smallholder farmers in Sub-Saharan Africa. Telecommun Policy. 2017;41:670–84. https://doi.org/10.1016/j.telpol.2017.05.010.
64. EFA Global Monitoring Report. Youth and skills: putting education to work. 2012. https://unesdoc.unesco.org/ark:/48223/pf0000218003. Accessed 7 Jul 2024.
65. BBC World Service Trust. African media development initiative. 2006. https://downloads.bbc.co.uk/worldservice/trust/pdf/AMDI/AMDI_summary_Report.pdfAccessed 7 Jul 2024. Accessed 7 Jul 2024.
66. Farm Radio International. Radio: a farmer's best friend. 2024. https://farmradio.org/why-radio/. Accessed 7 Jul 2024.
67. Farm Radio International. Farm Radio joins partnership to share communication for development stories. 2024. https://farmradio.org/farm-radio-international-joins-partnership-to-share-communication-for-development-best-practices/. Accessed 6 Jul 2024

68. Farm Radio International. Update from the Hangar: Uliza answers farmers' questions. 2018. https://farmradio.org/update-from-the-hangar-uliza-answers-farmers-questions/. Accessed 7 Jul 2024.
69. Farm Radio International. Tanzanian radio station runs competition. The prize? Trees. 2024. https://farmradio.org/tanzanian-radio-station-runs-competition/. Accessed 7 Ju 2024.
70. Farm Radio International. Interactive radio for ecologically sustainable agricultural practices: building resilient livelihoods through ecologically sustainable agriculture practices in central and northern Tanzania. 2024. https://farmradio.org/project/interactive-radio-for-ecologically-sustainable-agricultural-practices/. Accessed 7 Ju 2024.
71. Farm Radio International. Sustainable dialogue and knowledge sharing communication platforms: designing long-term e-extension platforms in Uganda. 2024. https://farmradio.org/project/sustainable-dialogue-and-knowledge-sharing-communication-platforms/. Accessed 7 Jul 2024.
72. Farm Radio International. Watch: Ugandan farmers share what they learned from the radio. 2024. https://farmradio.org/ugandan-farmers-share-what-they-learned-from-the-radio/. Accessed 7 July 2024.
73. Payne J, McCarthy S. African agriculture and ICT: an overview. 2010. https://pdf.usaid.gov/pdf_docs/PA00J7PV.pdf. Accessed 11 Jul 2024.
74. Odame HH, Okello D. Expanding the reach and benefits of digital agriculture. 2019. https://www.ictupdate.cta.int/en/article/expanding-the-reach-and-benefits-of-digital-agriculture-sid0e15806a2-f588-41aa-a5a7-a282f1b12628.html. Accessed 7 Jul 2024.
75. Batchelor S, Scott S, Manfre C, Lopez AV, Edwards D. Is there a role for mobiles to support sustainable agriculture in Africa? 2nd International Conference on ICT for Sustainability (ICT4S 2014). https://oxfamilibrary.openrepository.com/bitstream/handle/10546/325879/rr-icts-sustainable-agriculture-300714-en.pdf;jsessionid=7F9DE7BEE426CEBF9BC440BF94B7EB26?sequence=1. Accessed 16 Aug 2024.
76. Tsan M, Totapally S, Hailu M, Addom B. The digitalisation of African agriculture report (2018–2019). 2019. https://www.cta.int/cgspace.cgiar.org/bitstream/handle/10568/101498/CTA-Digitalisation-report.pdf. Accessed 8 Jul 2024.
77. Shalimov A. IoT in agriculture: 9 technology use cases for smart farming (and challenges to consider). 2023. https://easternpeak.com/blog/iot-in-agriculture-technology-use-cases-for-smart-farming-and-challenges-to-consider/. Accessed 6 Jul 2024.
78. Al-Ammary JH, Ghanem ME. Information and communication technology in agriculture: awareness, readiness and adoption in the Kingdom of Bahrain. Arab Gulf J Sci Res. 2022;42:182–97. https://doi.org/10.1108/AGJSR-07-2022-0113.
79. Kudama G, Dangia M, Wana H, Tadese B. Will digital solution transform Sub-Sahara African agriculture? Artif Intell Agric. 2021;5:292–300.
80. Ayim C, Kassahun A, Addison C, Tekinerdogan B. Adoption of ICT innovations in the agriculture sector in Africa: a review of the literature. Agric Food Secur. 2022;11:1–16. https://doi.org/10.1186/s40066-022-00364-7.
81. Onyeneke RU, Ankrah DA, Atta-Ankomah R, Agyarko FF, Onyeneke CJ, Nejad JG. Information and communication technologies and agricultural production: new evidence from Africa. Appl Sci. 2023;13:3918. https://doi.org/10.3390/app13063918.
82. Agwu EA Nwokorie UM. Challenges and opportunities for ICT adoption in agricultural extension. 2019. https://www.ictupdate.cta.int/en/article/challenges-and-opportunities-for-ict-adoption-in-agricultural-extension-sid03b7c751a-f2db-48c7-a5ed-40344e00e00a.html. Accessed 8 Jul 2024.
83. Bontsa NV, Mushunje A, Ngarava S, Zhou L. Utilisation of digital technologies by smallholder farmers in South Africa. S Afr J Agric Extension. 2023;51:104–46. https://doi.org/10.17159/2413-3221/2023/v51n4a15337.
84. International Telecommunication Union. Telecommunications/ICTs for rural and remote areas: Output Report on ITU-D Question 5/1 for the study period 2018–2021. 2021. http://handle.itu.int/11.1002/pub/80ec6ea7-en. Accessed 11 Aug 2024.
85. ITU. ITU-D SG1 Document SG1RGQ/11 from Rwanda: Universal Access and Service Fund as a pivotal for rural development. 2008. https://www.itu.int/md/D18-SG01.RGQ-C-0011. Accessed 13 Aug 2024.
86. Sakyi P Abdul-Fatawu M. Advice on beans: Farmerline's Mergdata farm-advice service in Ghana ICTs. CTA Technical Brief 13. Wageningen: CTA; 2017. https://cgspace.cgiar.org/server/api/core/bitstreams/95735a98-925b-43d3-8aa1-ce7d41af4364/content. Accessed 12 Jul 2024.
87. CTA. Making ICTs work for farmers: seven case studies. 2024. https://www.fao.org/e-agriculture/news/making-icts-work-farmers-seven-case-studies. Accessed 12 Jul 2024.
88. Gonnet J, Soungari S. Cashew on your phone N'kalô: RONGEAD's market-advice app in West Africa. CTA Technical Brief 9. Wageningen: CTA; 2000. https://publications.cta.int/media/publications/downloads/2000_PDF_J1Lc1oL.pdf. Accessed 12 Jul 2024.
89. Krell NT, Giroux SA, Guido Z, Hannah C, Lopus SE, Caylor KK, Evans TP. Smallholder farmers' use of mobile phone services in central Kenya. Clim Dev. 2020;13:215–27. https://doi.org/10.1080/17565529.2020.1748847.
90. Innovation is everywhere. 2022. Real-time stock price for African farmers: a case study of connected agriculture with M-Farm in Kenya. https://innovationiseverywhere.com/real-time-stock-price-african-farmers-case-study-connected-agriculture-m-farm-kenya/. Accessed 12 Jul 2024.
91. Kiger B, Adodo K. Getting fertiliser into farmers' hands. 2011. https://www.inter-reseaux.org/wp-content/uploads/p31-32_IFDC.pdf. Accessed 10 Jul 2024.
92. Martin C, Harihareswara N, Diebold E, Kodali H, Averch C. Guide to the use of digital financial services in agriculture. 2016. https://agrilinks.org/sites/default/files/guide_to_dfs_in_ag_web_final_0.pdf. Accessed 10 Jul 2024.
93. Awesome Communication. Cellulant to scale agrikore, mobile blockchain-based platform to more farmers. 2024. https://brandcom.ng/2018/05/cellulant-scale-agrikore-mobile-blockchain-based-platform-farmers/. Accessed 12 Jul 2024.
94. Agrikore Admin. Agrikore—blockchain powered agricultural ecosystem. 2018. https://medium.com/@agrikore/agrikore-blockchain-powered-agricultural-ecosystem-caef4094dd4e. Accessed 12 Jul 2024.
95. Viviane I, Masabo E, Joseph H, Rene M, Bizuru E. IoT-based real-time crop drying and storage monitoring system. Int J Distrib Sensor Netw. 2023. https://doi.org/10.1155/2023/4803000.
96. Al Zayed IS, Elagib NA, Ribbe L, Heinrich J. Satellite-based evapotranspiration over Gezira Irrigation Scheme, Sudan: a comparative study. Agric Water Manag. 2016;177:66–76. https://doi.org/10.1016/j.agwat.2016.06.027.
97. Gismalla YA. Satellite based ICT for improved crop production in Gezira Scheme. Fifth Nile Basin Development Forum 23–25 October, Kigali, Rwanda. 2017. https://www.itu.int/en/ITU-D/Regional-Presence/ArabStates/Documents/events/2017/IoTSMW/Presentations-SWM/Session4/Satellite%20based%20ICT%20for%20improved%20crop%20production%20in%20the%20Gezira%20Scheme%20-%20Sudan%20-NBDF.pdf Accessed 12 Jul 2024.

98. Batirbaev P, Kim T, Ma'ani R, Shim R, Singer J, Snyder M, Yawson F. Maize in Rwanda: a value chain analysis. United Nations Industrial Development Organization (UNIDO): Vienna. 2013. https://downloads.unido.org/ot/53/28/5328232/HABIMANA_EFR_FLD_AFR_RWA_RWA_2013.pdf. Accessed 12 Jul 2024.
99. Remme H. Rwanda smart satellite crop monitoring application. Presentation AfricaGIS Conference. 2019. https://geo-news365.esri-southafrica.com/Marketing/AfricaGISPresentations/Wednesdayam/Henk_Remme.pdf. Accessed 12 Jul 2024.
100. Tracex Technologies. Data-driven crop monitoring for agriculture. 2023. https://tracextech.com/crop-monitoring-the-future-of-farming/. Accessed 12 Jul 2024.
101. African Union Commission. Agenda 2063: The Africa we want. 2015. https://au.int/sites/default/files/documents/36204-doc-agenda2063_popular_version_en.pdf. Accessed 11 Aug 2024
102. Houghton JW. ICT and the environment in developing countries: a review of opportunities and developments. In: Berleur J, Hercheui MD, Hilty LM, editors. What kind of information society? Governance, virtuality, surveillance, sustainability, resilience. HCC CIP 2010 2010. IFIP Advances in Information and Communication Technology, 328. Springer, Berlin, Heidelberg. 2010; https://doi.org/10.1007/978-3-642-15479-9_23.
103. Yeboah-Assiamah E, Appiah D, Apeanti T, Tindan PD. Smallholder farmers' perception and adaptation to climate change in tropical African rural communities: a primer for collaborative policy intervention. In: Luetz JM Ayal D, editors. Handbook of climate change management. Springer, Cham. 2021; 5013–5032; https://doi.org/10.1007/978-3-030-57281-5_79.
104. The Rural Finance & Investment Learning Centre. Supporting smallholder farmers in Africa: a framework for an enabling environment. African Smallholder Farmers Group, London. 2013. https://www.rfilc.org/wp-content/uploads/2020/08/ASFG-Framework-Report.pdf. Accessed 17 Jul 2024.
105. Alliance for a Green Revolution in Africa (AGRA). Climate change and smallholder agriculture in sub-Saharan Africa.
106. Akinseye FM, Zagre I, Faye A, Joseph JE, Worou ON, Whitbread AM. Exploring adaptation strategies for smallholder farmers in dryland farming systems and impact on pearl millet production under climate change in West Africa. Front Agron. 2024;6:1428630. https://doi.org/10.3389/fagro.2024.1428630.
107. Muthee K, Duguma L, Majale C, Mucheru-Muna M, Wainaina P, Minang P. A quantitative appraisal of selected agroforestry studies in the Sub-Saharan Africa. Heliyon. 2022;8:9. https://doi.org/10.1016/j.heliyon.2022.e10670.
108. Kuyah S, Whitney CW, Jonsson M, et al. Agroforestry delivers a win-win solution for ecosystem services in sub-Saharan Africa. A meta-analysis. Agron Sustain Dev. 2019;39:47. https://doi.org/10.1007/s13593-019-0589-8.
109. Asongua SA, Le Rouxa S, Biekpeb N. Enhancing ICT for environmental sustainability in sub-Saharan Africa. Technol Forecast Soc Chang. 2018;127:209–16. https://doi.org/10.1016/j.techfore.2017.09.022.
110. Ikwunne T, Hederman L. ICT and the environment: strategies to tackle environmental challenges in Nigeria. In: Arabnia HR Deligiannidis L Shouno H Tinetti FG Tran QN, editors. Advances in computer vision and computational biology. Transactions on computational science and computational intelligence. Springer, Cham; 2021. pp. 497–507. https://doi.org/10.1007/978-3-030-71051-4_39.
111. Guja MM, Bedeke SB. Smallholders' climate change adaptation strategies: exploring effectiveness and opportunities to be capitalized. Environ Dev Sustain. 2024. https://doi.org/10.1007/s10668-024-04750-y.
112. African Union Development Agency (AUDA-NEPAD). Precision agriculture in action: utilising drone technology for enhanced soil mapping in African agriculture. 2022. https://www.nepad.org/blog/precision-agriculture-action-utilising-drone-technology-enhanced-soil-mapping-african. Accessed 10 Aug 2024.
113. Icenecdevnews. The role of smallholder farmers in biodiversity conservation and coping with climate change in Africa. 2024. https://medium.com/@kamtarawlings/the-role-of-smallholder-farmers-in-biodiversity-conservation-and-coping-with-climate-change-in-c08ab3134180. Accessed 11 Aug 2024.
114. Okoronkwo DJ, Ozioko RI, Ugwoke RU, Nwagbo UV, Nwobodo C, Ugwu CH, Okoro GG, Mbah EC. Climate smart agriculture? Adaptation strategies of traditional agriculture to climate change in sub-Saharan Africa. Front Clim. 2024;6:1272320. https://doi.org/10.3389/fclim.2024.1272320.
115. Averch C. ICT for agriculture. 2019. https://www.fhi360.org/wp-content/uploads/drupal/documents/resource-digital-dev-ict-agriculture.pdf. Accessed 10 Jul 2024.
116. Farm Radio International. Storytelling and climate change: a case study in climate change adaptation strategies. 2024. https://farmradio.org/storytelling-and-climate-change/. Accessed 8 Jul 2024
117. Farm Radio International. On-air for gender-inclusive nature-based solutions: addressing climate change and biodiversity loss in rural Africa through high-impact radio programs. https://farmradio.org/project/on-air-for-gender-inclusive-nature-based-climate-solutions/. Accessed 7 Jul 2024.
118. The African Union, African Development Bank, United Nations Development Programme and the United Nations Economic Commission for Africa. 2024 Africa Sustainable Development Report Reinforcing the 2030 Agenda and Agenda 2063 and eradicating poverty in times of multiple crises: the effective delivery of sustainable, resilient and innovative solutions. 2024. file:///C:/Users/ngulup/Downloads/asdr_2024_-_en.pdf. Accessed 11 Aug 2024.
119. Omari R, Jumpah ET, Arthur JO, Asabo R, Hagan E, Mahama A, Ameyaw RA, Baumuller FG. Use of information and communication technologies (ICTS) by intermediaries in the agriculture sector: Insights from Ghana. FARA Research Report 6. 2022. https://library.faraafrica.org/2022/06/30/use-of-information-and-communication-technologies-icts-by-intermediaries-in-the-agriculture-sector-insights-from-ghana/. Accessed 14 Aug 2024.
120. Garrity J. How ICTs enhance environmental sustainability projects. 2014. https://www.ictworks.org/how-icts-enhance-environmental-sustainability-projects/. Accessed 16 Aug 2024.
121. University of Southern California. How remote sensing saves the earth. 2021. https://gis.usc.edu/blog/how-remote-sensing-saves-the-earth/. Accessed 16 Aug 2024.
122. Kerry RG, Montalbo FJP, Das R, et al. An overview of remote monitoring methods in biodiversity conservation. Environ Sci Pollut Res. 2022;29:80179–221. https://doi.org/10.1007/s11356-022-23242-y.
123. Cho Y, Park KS. Designing immersive virtual reality simulation for environmental science education. Electronics. 2023;12:315. https://doi.org/10.3390/electronics12020315.

124. Eheazu CL, Ibanga MD. ICT-propelled innovations for environmental education in the 21st century: Positive transformations and some inherent health and safety challenges in the teaching and learning setting. Eur J Comput Sci Inf Technol. 2022;10:10–22.
125. Kateule R, Ghneim-Herrera T. Unveiling the controversies: ICTs in agriculture the challenges for Africa. 2024. https://www.southcentre.int/wp-content/uploads/2024/06/Unveiling-the-Controversies-ICTs-in-Agriculture-and-the-Challenges-for-Africa_report.pdf. Accessed 16 Aug 2024.
126. Nyakudya S, Jambo N, Madududu P, Manyise T. Unlocking the potential: challenges and factors influencing the use of ICTs by smallholder maize farmers in Zimbabwe. Cogent Econ Finance. 2024;12:2330431. https://doi.org/10.1080/23322039.2024.2330431.
127. International Telecommunication Union (2021). Telecommunications/ICTs for rural and remote areas. International Telecommunication, Geneva, Switzerland. 2021. https://www.itu.int/hub/publication/d-stg-sg01-05-1-2021/. Accessed 18 Aug 2024.
128. Abdulai AR, TettehQuarshie P, Duncan E, Fraser E. Is agricultural digitization a reality among smallholder farmers in Africa? Unpacking farmers' lived realities of engagement with digital tools and services in rural Northern Ghana. Agric Food Secur. 2023;12:11.
129. Alfonsi RM, Naidoo M, Gasparatos A. Stakeholder perspectives for information and communication technologies (ICTs) for sustainable food systems in South Africa: challenges, opportunities and a proposed ICT framework. Environ Dev Sustain. 2024. https://doi.org/10.1007/s10668-024-04838-5.
130. Warschauer M. Technology and social inclusion: rethinking the digital divide. MIT Press; 2004; https://direct.mit.edu/books/oa-monograph/1817/Technology-and-Social-InclusionRethinking-the. Accessed 8 Jul 2024.
131. Aker JC, Ghosh I, Burrell J. The promise (and pitfalls) of ICT for agriculture initiatives. Agric Econ. 2016;47:35–48. https://doi.org/10.1111/agec.12301.