Design and Implementation of a Farmer's Digital Information System for Sustainable Agriculture Among Smallholder Farmers in Tanzania

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THÈSE

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List of Publications and Academic Engagement

The following articles and academic deliverables were completed during the PhD program.

Peer-reviewed articles:

- **Mushi, G. E.**, Serugendo Di Marzo, G., & Burgi, P.-Y. (2022). Digital Technology and Services for Sustainable Agriculture in Tanzania: A Literature Review. *Sustainability*, *14*(4), 1–17. https://doi.org/10.3390/SU14042415
- **Mushi, G. E.**, Serugendo Di Marzo, G., & Burgi, P.-Y. (2022). Data management system for sustainable agriculture among smallholder farmers in Tanzania: Research-in-progress. *Information Technology for Development* *0*(0), 1–24. https://doi.org/10.1080/02681102.2023.2215528
- **Mushi, G.E.**; Burgi, P.-Y.; Di Marzo Serugendo, G. State of Agricultural E-Government Services to Farmers in Tanzania: Toward the Participatory Design of a Farmers Digital Information System (FDIS). Agriculture 2024, 14, 475, doi:10.3390/agriculture14030475.
- **Mushi, G.E.**; Burgi, P.; Serugendo, G.D.M. Designing a Farmers Digital Information System for Sustainable Agriculture: The Perspective of Tanzanian Agricultural Stakeholders. The Electronic Journal of Information Systems In Developing Countries 2024, 1–20, doi:10.1002/isd2.12344.
- **Mushi, G. E.**, Mwakifwamba, A. A., Burgi, P.-Y., & Di Marzo Serugendo, G. (2024). A Farmers' Digital Information System (FDIS) for Sustainable Agriculture Among Smallholder Farmers in Tanzania. *Information*, *15*(12), 816. https://doi.org/10.3390/info15120816

Talks

- **Gilbert E. Mushi**, Aaron Andrew Mwakifamba, Pierre-Yves Burgi, and Giovanna Di Marzo Serugendo. *"Implementation of Farmers Digital Information System (FDIS) for sustainable agriculture among smallholder farmers in Tanzania"*. NM-AIST International Conference on Tropical Horizon: Advancing Sustainability in Agriculture, Natural Resources, Environment and Technology" held from 17th to 19th July 2024 in Arusha, Tanzania.

Programme Committee and Reviewer

- Reviewer in the journal Heliyon 2024 (Impact Factor 3.4)
- Reviewer in Journal of Sustainable Features 2024 (Impact Factor 3.3)
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Research Assistant

- Project: *Think Before You Act: The Effect of Reflection on Business Decisions*. University of Zurich, Department of Economics, 2024-2025.

Abstract

Sustainable agriculture among smallholder farmers has the potential to ensure food security and alleviate extreme poverty in a rapidly growing population and the face of global climate change. Additionally, smallholder farmers contribute 70% of the world's food and employ more than one billion people, the majority of whom live in rural and semi-urban areas. However, this group of farmers faces various challenges in adopting sustainable agriculture. We conducted a literature review and a survey of key agricultural stakeholders in Tanzania to identify common challenges of smallholder farmers. It was revealed that smallholder farmers lack access to essential services, including subsidies, credit, insurance, government services, markets, and farming information.

In this thesis, we aim to design and implement a digital framework for smallholder farmers to access all essential services (subsidies, credit, insurance, government services, market, warehouse services, logistics services, quality farm inputs, and farming information) under one roof. Indeed, digital technology can play a significant role in digitizing the agricultural value chains (AVCs) of small-scale farmers in countries of the Global South. The use of advanced digital technologies in agriculture, including artificial intelligence (AI), the Internet of Things (IoT), blockchain, robotics, and big data, has enabled sustainable farming through increased production and income, as well as enhanced environmental conservation. However, these technologies are not accessible to smallholder farmers (the majority of whom reside in countries in the global South) as they require high investment capital, expertise, and well-established infrastructure. Although various digital services are available for smallholder farmers, the existing services often lack sustainability in the agricultural context and fail to meet their needs.

We employed the Design Science Research (DSR) method to design and provide a proof of concept of a digital platform that brings together all key agricultural stakeholders, enabling farmers to access all essential services throughout the complete farming cycle. Moreover, we conducted a literature review using the PRISMA guidelines to establish the state-of-the-art technology in agriculture and the use of ICT-based services by smallholder farmers in Tanzania. A survey method was employed as part of the DSR to collect stakeholders' opinions on the proposed digital artifact solution. The study follows the theories of Information and Communication Technology for Development (ICT4D), which posits that technological advancements should have a positive impact on people's lives by developing solutions that work well within the local context, rather than simply copying and pasting technology from other contexts, such as from developed to developing countries.

As a research contribution, we identified common challenges of smallholder farmers, designed and provided a proof of concept of a Farmers' Digital Information System (FDIS) that integrates services from different stakeholders, including farmers, agro-dealers, warehouses, logistics companies, subsidies, advisory services, market, credit, insurance, and government(permit) services. We expect our findings will help governments, the private sector, and policymakers to adopt and implement FDIS. This will make the agriculture sector more dynamic and help smallholder farmers participate in sustainable agriculture.

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Chapter 1

Introduction

1.1 Motivation

The world's food demand is expected to increase by 35% to 56% between 2010 and 2050 [1]. The question of how to eradicate global hunger and extreme poverty – Sustainable Development Goals (United Nations, 2015)– remains a major global societal challenge. Investing in smallholder farmers has the potential to eradicate food insecurity and extreme poverty globally. According to FAO, smallholder farmers produce 70% of the world's food and employ more than one billion people, the majority living in rural and semi-urban areas [2]. Smallholder farmers can potentially achieve sustainable agriculture through the use of Information and Communication Technologies (ICTs). However, such a group of farmers still faces many challenges despite the ICT-related efforts to help them access essential services for sustainable farming.

Indeed, digital technologies are central to the development of political, economic, and social aspects of human life. Advanced ICTs have enhanced work efficiency, increased production, reduced production time, and lowered service delivery and operational costs. Digital technologies have revolutionized the agriculture sector, promising increased productivity, income, and environmentally friendly practices – sustainable agriculture [3,4]. The recent digital technologies in the agricultural sector, also referred to as Industry 4.0 digital transformations, integrate the Internet of Things (IoT), cyber-physical systems, Artificial Intelligence (AI), Big Data, Machine Learning, and Cloud computing with agricultural machinery [5]. It can be categorized into three phases, which are (1) data collection tools, particularly the IoT, (2) data management and analysis, such as Farm Management Information System (FMIS), (3) decision making and variable rate technology (actuation) [6]. These advanced digital technologies optimize farm inputs, facilitate accurate decision-making, minimize production risks through early warning systems, control pests and diseases, reduce production costs, and increase yields, thereby promoting sustainable agriculture. However, these cutting-edge technologies are primarily used by large-scale farmers in the global North. Many smallholder farmers, particularly in developing countries, lack access to these technologies due to the high cost of operation, a lack of expertise, poor infrastructure, and government policies that hinder the development of ICTs. The available digital technologies for smallholder farmers include simple mobile applications and web technologies designed for specific crop value chains within a particular country, which often lack components of sustainable agriculture [6]. Therefore, this study needs to assess the needs of smallholder farmers, design and implement a digital platform to meet those needs, with a particular focus on promoting the adoption of sustainable agriculture in Tanzania.

1.2 Thesis Research Questions

In the digital era, ICTs are an integral part of the agricultural sector, and their adoption by all types of farmers globally is essential for sustainable agriculture. While countries in the global north lead in the use of sophisticated technologies in agriculture, those in the global south lag behind due to a lack of expertise, inadequate government ICT policies, and insufficient infrastructure. However, ICTs could be designed and implemented to fit the needs of the local environment, rather than copying and pasting technologies from developed to developing countries. Therefore, this thesis focuses on the central research question (TRQ):

What comprehensive digital platform could be designed and implemented to enable smallholder farmers in Tanzania to access all the essential services of a complete farming cycle via a single access point?

Such a digital platform needs to address the common challenges faced by smallholder farmers throughout the entire farming cycle for sustainable agriculture in Tanzania. The following research questions are critical to answering the central thesis question (TRQ).

- What are the common challenges facing smallholder farmers, and what services are needed for a complete farming cycle? **(RQ1)**
- What digital platform could be designed and implemented to address the challenges of the smallholder farmers in Tanzania? **(RQ2)**
- What is the applicability of the developed digital framework in solving the existing smallholder farmers' challenges in Tanzania? **(RQ3)**
- What are the prerequisite infrastructures, other capabilities, and resources for such a framework to be successfully implemented and sustainably operated? **(RQ4).**

Although the platform is designed to address the challenges faced by smallholder farmers in Tanzania, the design framework could be adapted for use by many other developing countries. As ascertained by Chandra and Collis [7] the challenges of smallholder farmers are more similar across developing countries. Therefore, the platform designed will potentially be helpful in many other developing countries. Such a platform could increase farm production and profitability while preserving the environment.

1.3 Thesis Objectives

The primary objective of this thesis is to design and implement a digital platform that enables smallholder farmers in Tanzania to access all essential services throughout a complete farming cycle via a single access point. The following specific objectives are critical to achieving the main objective:

- To identify common challenges facing smallholder farmers and the services needed for a complete farming cycle **(TO1).**
- To design and implement a digital platform that addresses the challenges of the smallholder farmers in Tanzania **(TO2)**.
- To assess the applicability of the implemented digital platform in solving the existing smallholder farmers' challenges in Tanzania **(TO3)**.
- To establish the prerequisite infrastructures and other capabilities and resources for the successful and sustainable implementation of the digital platform in Tanzania **(TO4)**.

1.5 Thesis Structure

This PhD thesis is based on peer-reviewed articles; it is a summary of five journal articles, which are fully accessible in the annexes attached to this work. The thesis is organized into eight chapters, including this introduction. Chapter Two surveys related work on the use of digital technologies in agriculture, focusing on the most advanced technologies and those used by smallholder farmers in the global south countries, with a case study of Tanzania. Chapter Three explains the research methodology used throughout the project, detailing the flow of activities, techniques, and approaches. Chapter Four presents the findings of the survey of agricultural stakeholders in Tanzania, which identified their challenges and opinions regarding the proposed solution. Chapter Five covers the design and prototype of the Farmers' Digital Information System (FDIS). This digital platform addresses the common challenges faced by smallholder farmers in adopting sustainable agricultural practices in Tanzania. Chapter Six presents the applicability (illustration) of FDIS in addressing the challenges faced by smallholder farmers in Tanzania. Chapter Seven provides a discussion of the prerequisite infrastructure, other capabilities, and resources for the successful and sustainable implementation of FDIS in Tanzania. The thesis concludes with Chapter Eight, which summarizes the scientific contributions and suggests future research directions.

Chapter 2

Related Work

This chapter discusses relevant research of the study. Firstly, this chapter highlights agricultural revolutions and transformations, demonstrating how digital technologies have become a critical tool for sustainable agriculture. Secondly, it presents the latest digital technologies in agriculture and the disparity of the adoption among different farmer categories and regions globally. Thirdly, the chapter examines the status of digital technologies in agriculture in developing countries, with a particular focus on sub-Saharan Africa. Fourthly, the chapter discusses the adoption and use of digital technologies in the agriculture sector in Tanzania, highlighting the gaps and the need for a local context digital platform to help smallholder farmers participate in sustainable agriculture.

2.1 Agriculture Revolutions and Transformations

Agriculture has always been a critical component of human existence and development. This sector has undergone various revolutions and transformations to meet the needs of the growing population, and has also influenced the Industrial Revolution [8]. Liu et. al [9] categorized agriculture revolution and transformation into four, along with the industrial revolution, which has been powered by advanced digital technologies. The first category is agriculture 1.0 between 1784 and 1870, where farmers used simple tools such as a hand hoe, with most work done manually or powered by animals. The second is agriculture 2.0, also known as a "green revolution" from the 1950s, which involved the use of farm machinery that farmers manually operated. The use of fertilizer and pesticides was introduced in this era. The third category is agriculture 3.0 from the 1990s, marking the beginning of digital technology in agriculture, referred to as "precision agriculture" (after the discovery of the first programmable controller in 1969). It brings together researchers and industrial groups that employ digital technologies for yield monitoring, guidance systems, and variable-rate applications. The fourth category is Agriculture 4.0, introduced in 2017, which represents an advanced form of precision agriculture, also referred to as "smart farming or agriculture". It is highly autonomous farming, a trustworthy food supply, and ubiquitous agriculture sensing.

Agriculture 5.0, a new paradigm recently reported in the literature, aims to address various issues that Agriculture 4.0 failed to resolve [10]. According to Bissadu et al. [10] and Haloui et al. [11], agriculture 5.0 is a new approach that blends modern technology and human–machine interaction into farming practices. Indeed, it is a synergy between the creative ingenuity of human experts and the precision, intelligence, and power of advanced machinery. Therefore, while agriculture 4.0 focuses on automating agricultural activities and operations, which reduced human intervention in the production process by enhancing mass performance and productivity, exploring machine learning (ML)-based intelligence between applications and devices, agriculture 5.0 is envisioned as a collaboration between the original innovation of human professionals and powerful, intelligent, and precise machinery. It aligns with Industry 5.0, which reintroduces the human element into manufacturing, thus allowing customers to prefer customized and personalized products based on their preferences and requirements. While Agriculture 4.0 embraces autonomous cyber-physical systems powered by AI and IoT, Agriculture 5.0 focuses on precision crop monitoring with minimal human intervention, supported by AI, machine learning, and robotics [12]. Figure 1 illustrates the timelines of agricultural revolutions from Agriculture 1.0 to Agriculture 5.0.

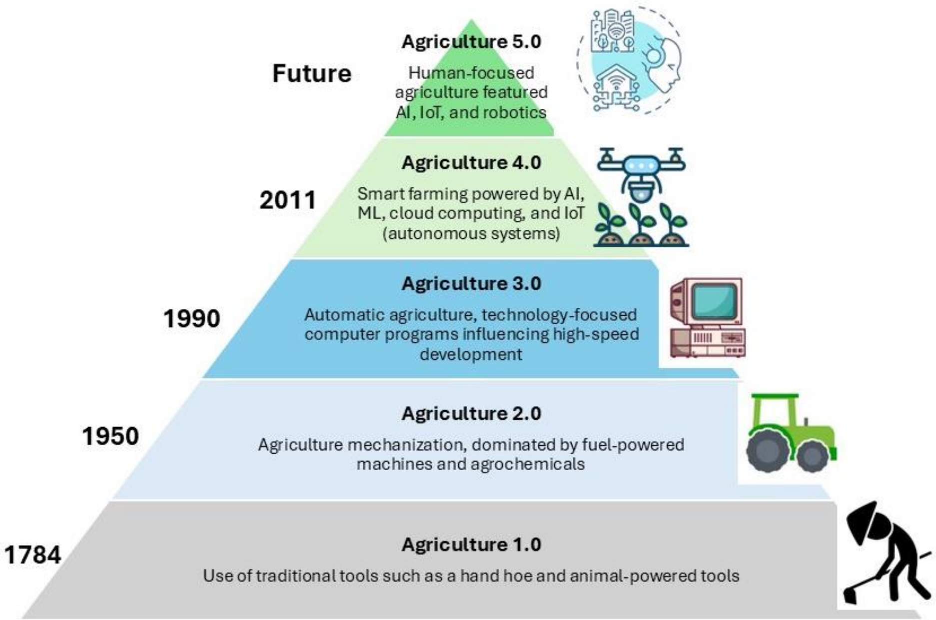

Figure 1 Timelines of agricultural revolutions from Agriculture 1.0 to Agr. 5.0, inspired by [10–12]

2.2 Advanced Digital Technologies in Agriculture

The current industry 4.0 digital transformation in agriculture integrates IoT, cyber-physical systems, AI, Big Data, Machine Learning, and Cloud computing [13]. These highly sophisticated and integrated systems have ensured sustainable agriculture through effective farm management, automation of logistics, and optimized supply chains. It is more common in precision agriculture, whereby innovative ICT solutions and IoT components, such as sensors, monitor spatial and temporal variability in farm production [13,14]. Site-specific farm management provides an understanding of soil and crop characteristics unique to each field, thus enabling farmers to apply farm inputs (such as irrigation, fertilizers, pesticides, and herbicides) in small portions where needed for the most economical production [15]. Controlled farm inputs increase farm productivity and profitability, conserve the environment, and promote sustainable agriculture development [16]. Precision agriculture and smart farming rely on data management to make valuable decisions. The embedded digital technology components can be categorized into three phases: (1) data collection (IoT), (2) data management and analysis, and (3) decision making and variable rate technology (actuation) [5].

2.2.1 Data Collection—IoT

IoT in agriculture uses sensors—devices used to collect data from the field for easy monitoring of the crops and other digital tools to collect essential data for profitable decision-making in farming [5]. The sensors are mounted in the mobile farm machinery or fixed in the field, such as a local weather station. For instance, Kilin [17] utilized a network of automated stations in the vineyards to identify areas affected by pathogens, enabling site-specific pesticide applications. The stations collect real-time data, including airborne particles, temperature, and relative humidity of the air and soil, solar irradiance, spores, and leaf humidity. AI is then used to analyze the spatio-temporal heterogeneity data based on optical particle counters (OPC) to identify areas affected by the pathogen (i.e., Plasmopara viticola) [17]. The results enable farmers to apply pesticides in specific field zones, resulting in cost-effective, healthy products and environmentally friendly farming practices. Saiz-Rubio [5]: remote sensing, aircraft, and proximal sensing. Remote sensing, most often satellites, has been an essential tool for collecting field data in smart farming. The satellites used to provide agricultural data include WorldView 2 and WorldView 3 multispectral satellite sensors, which utilize the Normalized Difference Vegetation Index (NDVI) standard [18,19]. Furthermore, the European Sentinel 2 satellite system, which gives access to 10 m 4-band multispectral data for "NDVI imagery of soil and water, covers the Earth every 10 days; the American Landsat satellites provide spectral data from the Earth every 16 to 18 days [5,19].

Aircraft sensing, usually "remotely piloted aircraft (RPA) and unmanned aerial vehicles (UAV)" such as drones, capture field data at a closer distance of up to 100 m, contrary to the order of 700 km of satellites [20]. Although aircraft sensing is expensive and requires high skills to generate quality field data, they are flexible and can reach field areas where other equipment cannot. Proximal sensing is the latest technology based on "autonomous ground systems", promising a new agriculture transformation [20]. In comparison to remote and aircraft sensing, proximal sensing monitors the crop on the ground at less than 2 m between the crop and the sensor [5]. The payload of sensors is placed in ground vehicles that move around the field to collect accurate and quality data from the crops. Proximal sensing allows a real-time application, such as applying fertilizer where needed and spraying herbicides and pesticides where weeds or pests have been detected [21].

Robotic technology in farming is another area of interest and part of proximal sensing, where unmanned ground vehicles (UGV) collect data and manage various farm activities [22]. The farmers use UGVs for soil analysis, seeding, transplanting, harvesting, and crop scouting. Thus, UGVs allow a continuous field data collection process to monitor crop status and growth conditions [23]. VineRobot and Vinescount, funded by the European Commission, are examples of robotic technologies in smart farming that monitor vineyards by collecting data from the vines' canopy and creating water and nutrition status maps [5]. Industries manufacturing agricultural tools are also producing scouting robots. For example, Rowbot Systems LLC of the USA introduced a multitask robotic platform to map crop growth zones, apply fertilizer, and perform other related tasks [24]. Another example is the robot Oz, the autonomous weeding and seeding [25].

2.2.2 Data Management and Analysis

A digital system receives data from different IoT devices and helps generate meaningful information for production. Large-scale and commercial farmers utilize farm management information systems (FMIS) to collect, store, analyze, and manipulate data in precision and smart farming. FMIS enables farmers to manage various farming activities from the initial planning stage to harvest and record important information about the performed activities [26]. Farmers can extract information, such as field maps, to determine the crops and field conditions necessary for actions related to minimizing resource use, compliance with standards, and ensuring the quality of agricultural production. There are different FMIS on the market (most are proprietary) with various features to manage farm-generated data. The systems manage farm operations based on data acquired and processed automatically for planning, monitoring, supporting decision-making, and keeping valuable records [27]. Hrustek [13], mentioned that FMIS records critical information, including "harvests and yields, profits and losses, farm task scheduling, weather prediction, soil nutrients transport, and field mapping". A few examples of FMIS include ADAPT, Agrivi, Agroptima, and Farmleap, which are owned primarily by companies from developed countries. More advanced FMIS provides early warning, financial management, and integrates other actors such as input suppliers and product distributors.

2.2.3 Decision-making and Variable Rate Applications

Farmers need to decide on the vast volume of collected data, considering different field parameters. Managing such complex data manually is difficult, time-consuming, and prone to ineffective decision-making [13]. Hrustek [13], added that farmers could use AI and machine learning to support decision-making in agriculture through available big data. Wolfert [28], argued that agriculture has many areas for applying different AI technologies. For instance, Giusti and Marsili-Libelli [29] developed a decision support system (DSS) based on fuzzy logic to manage irrigation, considering the soil characteristics and type of crop. Additionally, Bazzani [30] developed a DSS that analyzes short- and long-term availability of water based on soil type, machinery, and irrigation systems. Furthermore, Rupnik et al. [31], developed AgroDSS, a cloud-based DSS that allows farmers to upload data or integrate with FMIS through an application programming interface (API) to get different output decisions, such as farm pest management.

Variable rate technology (VRT) has made it possible for decisions to be made autonomously. According to Hrustek [13], actuation refers to the execution of activities in the field following decision-making based on collected data. VRT includes robots used to perform different farm activities (farm preparation, planting, pest and weed control, fertilization, harvesting) previously conducted by human labor or conventional farm machines [18,29]. The variable-rate device receives commands from a computerized DSS. It performs various farming tasks, such as applying fertilizers, pesticides, and herbicides in specific field zones as needed (real-time applications), and harvesting [32]. A few examples of VRT machines include the Automated Yield Monitoring System II (AYMS II), which features unique "eye" color cameras and real-time kinematics-GPS for wild blueberry harvesting [3]. A sensor-based variable rate nitrogen fertilizer (VRNF) measures nitrogen using a multispectral sensor and a fertilizer spreader mounted on a tractor, enabling real-time application that conforms to the measured nitrogen in the crop [33]. The CLAAS VRT is used to apply nitrogen fertilizer, compatible with the "ISARIA" sensor [13]. VRT increases production and preserves ecological balance through the efficient use of farm inputs, such as reduced crop fertilizer and chemicals [34]. Figure 2 presents the three main categories of the smart farming data life cycle.

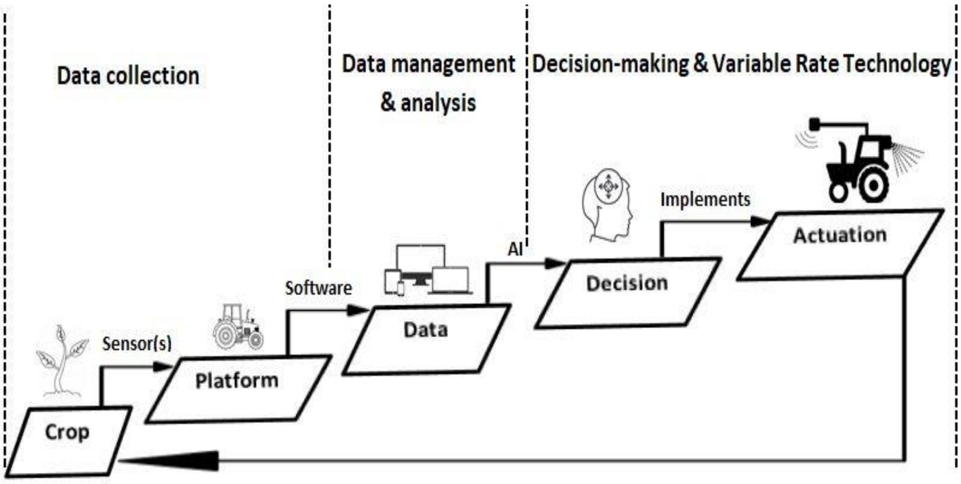

Figure 2. Smart farming data life cycle [6]

These components work autonomously to optimize farm inputs and yield forecasts, collaborating with other stakeholders such as service providers and the market, thereby improving sustainability in agriculture. In the Global North, digital farming platforms are usually owned by private companies that farmers and other stakeholders can subscribe to, normally for a fee. While these advanced digital platforms may not apply to developing countries (for example, 365FarmNet, [35]), aspects such as the ability to record data even without Internet access and data protection strategies could be helpful for platforms being considered in the developing world.

2.3 Digital Technologies and Smallholder Farmers in the Global South

Many digital agricultural solutions have been developed in low- and middle-income countries, covering various aspects of farmers' socio-economic development. They include strengthening the market for farm products through e-markets [34], improving agricultural extension services [35, 36], and disseminating agricultural information to enhance farming and decision-making [36–39]. These solutions alleviate several challenges faced by farmers, such as combating counterfeit farm inputs [41], accessing financial services and mobile payments [42–44], and access to farm insurance [40].

The adoption of precision agriculture by smallholder farmers in developing countries holds promise for the future, but as already noted, these advanced IT projects are still in their infancy. [41]. Also, each country has various digital services for smallholder farmers, ranging from simple mobile applications to Web-based digital solutions, for instance, the Association for People of Haryana's (AFPOH) e-governance-mediated agriculture project in India [42], the Kenyan Agriculture and Livestock Research Organization's (KALRO) mobile applications project for different value chains [43] and the online fertilizer recommendation to farmers in Bangladesh

[44]. Digital solutions in developing countries often face sustainability issues and typically address a specific farming problem or value chain. Thus, a digital framework solution for smallholder farmers that addresses common challenges throughout the entire farming cycle via a single access point is lacking. Such a digital framework will contribute to the development of farmers economically through increased production and income, and strengthen agricultural value chains in developing countries. Therefore, unlike Agriculture 4.0, which offers services throughout the entire farming cycle, digital services for smallholder farmers typically only address a single problem. These solutions encompass financial services, market services, extension services (including knowledge and information), and e-Government services in agriculture.

2.3.1 Credit and Insurance Services

Smallholder farmers face the challenge of access to financial services, which affects agricultural production and the income of many rural communities in developing countries [45]. Digital technology is a crucial tool for enhancing access to finance and promoting the commercialization of smallholder agriculture. A study on the awareness and use of m-banking (mobile banking) shows that most smallholder farmers in Kenya use the technology to access finance for agriculture-related activities [46]. Kirui [46], concluded that m-banking enables smallholder farmers to access investment capital for purchasing quality seeds, farm machinery, fertilizer, and pesticides, leading to increased production and income. The AFPOH is an ICT-based agriculture initiative in India that enables most smallholder farmers to access finance for improved agriculture [42]. Different countries are embracing digital technology to facilitate the commercialization of smallholder agriculture as a poverty alleviation and food security strategy.

Furthermore, agricultural insurance is an essential service for smallholder farmers. The farmers commonly encounter various production and market risks, which lower their income and ability to produce year after year. Hess and Hazell [47], mentioned natural disasters such as extreme droughts, floods, hurricanes and pest outbreaks are common risks for smallholders. The risks have severe impacts on economic development, leading to extreme poverty. In the past, governments and organizations have designed several insurance programs to help small farmers adopt sustainable agricultural practices. However, agrarian stakeholders and organizations consider index-based agricultural insurance to be more effective for smallholder farmers in developing countries [48,49]. Still, the majority of smallholder farmers, particularly in Africa, have no access to insurance. For instance, approximately 650,000 farmers have access to insurance in Africa out of around 40 million smallholder farmers in Sub-Saharan Africa alone [47]. The current trend of climate change requires financial investment for agricultural transformation, including increasing availability and access to credit and insurance by smallholder farmers [50].

2.3.2 Knowledge and Information Services

The dissemination of agricultural information and knowledge is a crucial step towards improved farming. Most smallholder farmers lack farming information and knowledge, so they rely on friends, family, and experience, resulting in low production [51]. Access to data throughout the entire farming cycle, from farm preparation to inputs, finance, harvesting, and marketing of products, creates high value in the commercialization of smallholder agriculture. Ali et al. [52] examined the critical information needs of farmers in Pakistan and developed a digital solution to deliver weather forecasts, pesticide, and fertilizer information. E-agriculture initiatives in India emphasize disseminating information to most rural smallholder farmers through ICT, including management information systems, knowledge management systems, and expert systems [42]. Sanga et al. [53] developed an information dissemination system to enable smallholder farmers to access critical farming information and knowledge from experts, bridging the gap of extension services through ICT. Scientists and organizations have developed mobile applications to disseminate information about different crops and livestock. For instance, KALRO in Kenya has produced more than fourteen mobile applications for crops and livestock to help farmers access information and adopt modern farming techniques for increased production [43].

2.3.3 Market Services

The market for farm products is a critical component of the agricultural value chain, which faces various challenges for smallholder farmers. Contrary to the large and medium scale farmers who use advanced FMIS to automate essential farming activities, including the market [54], smallholder farmers lack market information about their products. As such, the middlemen (intermediaries) utilize this gap to help farmers reach the market for their produce; however, farmers do not earn the deserved income, thereby affecting sustainability [55,56]. Although in its infancy, contract farming in Tanzania was introduced to ensure farmers get a reliable market for their farm products [57]. Some studies are focusing on the importance of advanced technology in developing countries, such as precision farming [46] and blockchain technology in agriculture to ensure transparency, especially in contract farming [58]. Indeed, advanced digital technology cannot be an immediate solution to the challenges faced by smallholder farmers in developing countries due to low digital literacy and limited infrastructure. However, designing solutions using simple digital technologies, such as mobile applications, that address essential challenges throughout the entire farming cycle could lead to sustainable agriculture [6].

2.3.4 e-Government Services in Agriculture

Governments play a crucial role in developing various economic sectors, including agriculture. For a long time, most governments have provided multiple services in agriculture, most often through subsidies to smallholder farmers, searching for international markets, and extension agents responsible for linking with farmers [59]. Governments are embracing the use of ICTs in agriculture by digitizing some of their services and improving digital infrastructure to meet farmers' needs. Governments play a central role in monitoring, controlling, and bringing together agricultural stakeholders to facilitate service delivery through a single access point, thereby promoting digital technology for sustainable agriculture at the national level. Organization for Economic Co-operation and Development (OECD) [60] mentioned that ICT promotes government transparency and accountability to the community. Ntaliani et. al. [61] assessed the potential of e-government in the agricultural sector, which suggests that the government should use the e-government model to offer services to farmers and rural communities. Therefore, e-government provides the government with opportunities to deliver multiple, coordinated, and timely services under one roof through a network of agricultural actors. A few examples include various digitization projects in India [42,62], Kenya [43], and Bangladesh [44].

2.4 Sustainable Agriculture

According to Bhakta et al. [3], Giray and Giray et al. [4], sustainable agriculture refers to agricultural practices that ensure long-term increased farm production and farmers' income while protecting the environment. Precision agriculture and smart farming present a high level of sustainability using the most cutting-edge technology to control farm inputs such as fertilizers, irrigation, herbicides and pesticides [5]. Farmers apply farm inputs to only parts of the field that need, thus improving product quality, reducing input cost, increasing productivity, preserving the environment, and achieving economic and environmental sustainability [4,13]. Social sustainability in agriculture results from economic and ecological sustainability. Social sustainability refers to the availability of enough food for all people, animals, and plant species in the world [4]. Social sustainability in agriculture focuses on the quality of life, with indicators such as the creation of employment, reducing rural migration, and increasing local food production. Cultural sustainability in agriculture is another component that emphasizes the integration of cultural values, knowledge, and practices into the farming system to ensure long-term ecological, social, and economic sustainability. Literature on sustainable agriculture mainly focuses on agricultural operations and business models for increased profit while minimizing the use of agrochemicals to promote a healthy environment and higher production quality. The new "fog computing model" is useful for a clean environment in smart agriculture. Unlike cloud computing, the fog computing model reduces carbon emissions through energy-efficient digital hardware and renewable energy resources since data is processed closer to where it is collected [63].

In addition to previous sustainability approaches, this thesis focuses on the fundamental component of sustainable agriculture in the digital era: the sustainability of infrastructures and resources that support digital agriculture services for smallholder farmers. Thus, this thesis categorizes sustainable agriculture into three main topics: (i) sustainability of the infrastructure and resources offering digital services, (ii) economic sustainability—long-term increased productivity and profitability, and (iii) environmental sustainability—conservation ecology and minimizing ICT pollution through green computing (Table 1).

Table 1. Sustainable agriculture

Components	Definition/Meaning	Characteristics
ICTs Infrastructure and resources sustainability	The ability to maintain digital systems (hardware and software) and human resources (such as IT specialists, services providers and data collectors) for long-term services to farmers.	Regular maintenance Hardware replacement Software upgrades Budget for human resources and service providers Energy consumption Environmental impact of production and disposal of ICT hardware
Economic sustainability	Refers to a long-term increased farm production that eventually increases farmers' income.	Less input cost High production Good market price Increased farmers' income
Environmental sustainability	Refers to actions taken consistently for conservation ecology by minimizing harmful agriculture and ICTs' environmental impacts.	Less use of agrochemicals Use of fortified agrochemicals Use of renewable energy Energy-efficient hardware Use of recyclable hardware Less carbon emission from data centers

Source: Mushi et al. [6]

2.5 Digital Technology and Agriculture in Tanzania

In Tanzania, the government introduced e-services in agriculture to address some critical challenges faced by farmers. These include M-Kilimo, a call center, and the Digital Fertilizer Subsidy Digital System (DFSDS). M-Kilimo is a mobile application and a web-based extension service freely accessible to farmers for consultations on various issues related to agriculture (crop farming, livestock keeping, and fishing). The service was launched in May 2020 and is available on the Android operating system via Unstructured Supplementary Service Data (USSD) and on a website (http://exts.kilimo.go.tz) (accessed January 23, 2025). The MoA stated that M-Kilimo aimed to reach a large number of farmers nationwide with extension services. The services that farmers and other stakeholders can access on this platform include price information, the sale and purchase of agricultural products, and advisory services [64].

The Tanzanian government, through the MoA, launched a call center service in July 2022 to enable wider access to extension services for the majority of farmers. This was done to improve the inclusion of farmers who were unable to access the M-Kilimo application due to various reasons, such as digital illiteracy or poor Internet service in rural areas. Farmers are free to call the center with any questions they may have about the agriculture sector and receive rapid answers or a callback. All stakeholders can ask questions about the agriculture sector, whether they relate to crops, livestock, fishing, marketing, or agro-inputs, among other topics. Since independence, the Tanzanian government has maintained its subsidy program, particularly for fertilizers, to support farmers. Until recently, subsidy distribution was performed manually through the local government from the ministry level to regional, district, ward, and village administrations. This distribution process faced numerous challenges, including corruption, cheating, and fraud, which led to limited access to subsidies for many smallholder farmers. Large- and medium-scale farmers used corrupt leaders to access substantial amounts of subsidies, while denying access to most smallholder farmers. On the other hand, agro-input traders used the opportunity to export subsidized inputs to neighboring countries illegally [65]. Therefore, this method of distribution was ineffective and had little impact on the farming community. The government has recognized the potential of digitizing the subsidy distribution service to mitigate or eliminate the challenges associated with the traditional distribution method. In September 2022, the government launched the DFSDS to manage the distribution of fertilizer to all farmers in Tanzania. The DFSDS is managed by a government agent, the Tanzania Fertilizer Regulatory Authority (TFRA), and services are housed in the extension services section of the MoA [64].

2.6 Research Gaps

The literature review presented in this chapter provides a theoretical framework that guides the design and implementation of digital information systems for farmers in sustainable agriculture among smallholder farmers. The reviewed related works examined the potential of digital technologies in the agricultural sector towards achieving sustainable agriculture, increased production, and income while conserving the environment. Despite the potential of advanced digital technologies, smallholder farmers continue to face challenges in adopting sustainable agricultural practices. This thesis seeks to address the gaps in the use of digital technology among smallholder farmers for sustainable agriculture by doing the following.

First, despite the introduction of various digital technologies to smallholder farmers in different countries, challenges persist in achieving sustainable agriculture. Many smallholder farmers residing in rural and semi-urban areas of developing countries struggle to utilize advanced digital technologies in agriculture due to limited infrastructure, a lack of expertise, low digital literacy, and inadequate financial capacity. There are many ICT solutions developed to address challenges in agriculture and smallholder farmers, ranging from simple mobile applications to web-based digital platforms. However, the existing ICT solutions for smallholder farmers, particularly in developing countries, address a specific challenge that requires farmers to coordinate various solutions to obtain services throughout the complete farming cycle. Therefore, designing a digital solution that smallholder farmers can access all essential services throughout the whole farming cycle requires identifying their everyday challenges. This is linked to Thesis Objective One **(TO1):** *to identify common challenges facing smallholder farmers and the services needed for a complete farming cycle*. Moreover, it answers research question one: *What are the common challenges facing smallholder farmers and the services required for a complete farming cycle? **(RQ1)***.

Second, a digital solution that addresses the identified common challenges of smallholder farmers needs to be designed and implemented, allowing farmers to access all essential services within a complete farming cycle under one roof, thereby promoting sustainable agriculture. The digital artifacts should be developed within the context of the problem environment to meet the local requirements. This is directly related to Thesis Objective Two: to design and implement a digital platform that addresses the challenges faced by *smallholder farmers in Tanzania **(TO2)***. And the second research question: *What digital platform could be designed and implemented to address the challenges of the smallholder farmers in Tanzania? **(RQ2).***

Third, the designed digital platform should be applied to solving the identified challenges of the smallholder farmers for its validity. There are various ways to assess the applicability of the designed artifact, including simulation, proof of concept, prototyping, pilot implementation, and illustration. It is linked to thesis objective three*: to assess the applicability of the implemented digital platform in addressing the existing challenges faced by smallholder farmers in Tanzania (TO3), and research question three: What is the applicability of the designed digital framework in solving the existing challenges faced by smallholder farmers in Tanzania? **(RQ3).***

Fourth, the successful implementation of a sustainable digital platform requires careful consideration of several supporting factors. These include reliable ICT infrastructure, financial resources, expertise, legal considerations, and other factors that ensure the sustainability of the digital platform in a particular environment. This is achieved through Research Objective Four, which seeks to establish the prerequisite infrastructures and other capabilities and resources necessary for the *successful and sustainable implementation of the digital platform in Tanzania **(TO4)***. Moreover, it is linked to question four of the research: What are the prerequisite infrastructures and other capabilities and resources necessary *for such a framework to be successfully implemented and sustainably operated? **(RQ4).*** Figure 3 presents a conceptual framework for sustainable agriculture in Tanzania, highlighting the challenges(gaps) of smallholder farmers and future solutions.

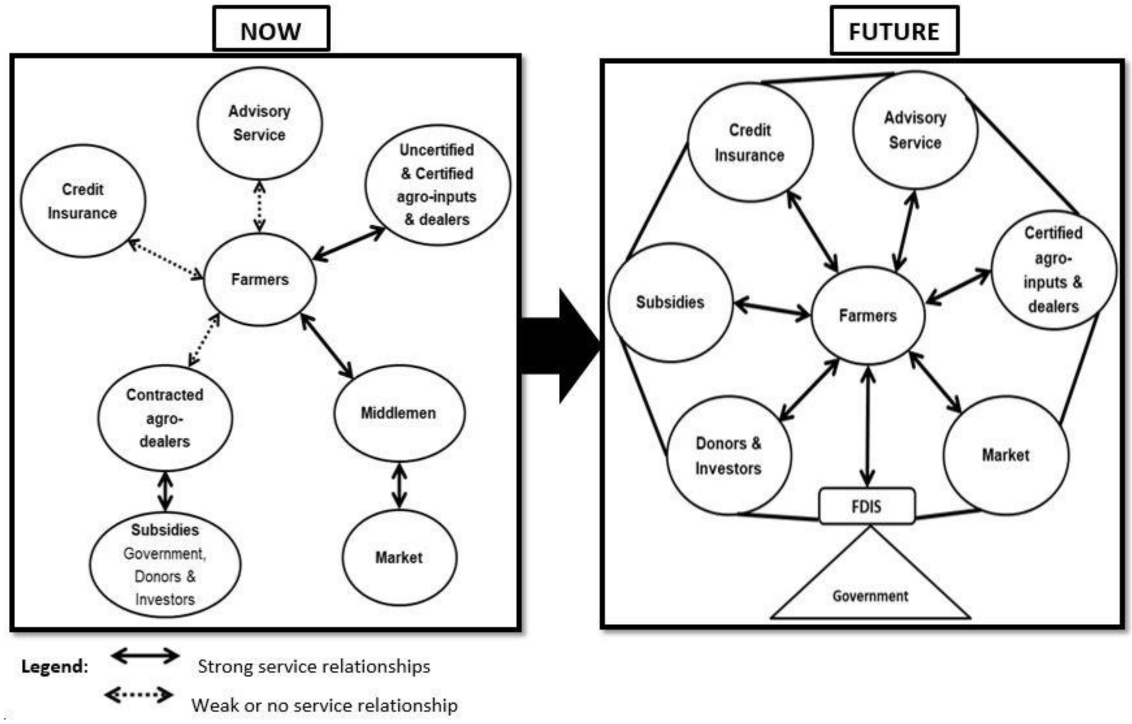

Figure 3. A conceptual model for sustainable agriculture in Tanzania [66].

In the subsequent chapters, we will explore the materials and methods designed to address the identified research gaps, presenting the findings on what a comprehensive digital platform could be designed and implemented to enable smallholder farmers in Tanzania to access all the essential services of a complete farming cycle via a single access point.

Chapter 3

Methodology

3.1 Introduction

In this thesis, we aim to design and implement a digital platform that enables smallholder farmers in Tanzania to access all essential services of a complete farming cycle through a single access point. Indeed, digital technology has the potential to achieve sustainable agriculture among smallholders when carefully designed to interact with the problem context and enhance the development of an effective and efficient information system.

The designed methodologies reflect the theoretical and practical implications related to the specific objectives (ROs) and research questions (RQs) of this thesis. The research questions are tailored to a step-by-step process, with each question contributing to the achievement of the central thesis objective. This is to ensure that the thesis findings contribute to both the academic knowledge and the practical implications of implementing a digital platform for smallholder farmers to participate in sustainable agriculture. This chapter presents Design Science Research (DSR) as a general methodology for this thesis. We customized a DSR method to answer each research question, thereby involving other techniques, including PRISMA guidelines, a survey, and SWOT analysis, which underpin this research and provide an extensive framework to achieve the thesis's objectives.

The DSR, as a general methodology followed in this thesis, is presented in Section 3.2. Section 3.3 describes other methods used to answer some of the specific research questions. Then, section 3.4 explains the SWOT analysis of the methodology.

3.2 Design Science Research Methodology

This thesis employed the DSR method to design and implement a digital platform that brings together all key agricultural stakeholders, enabling farmers to access all essential services throughout the complete farming cycle. The thesis follows the theories of ICT4D, which posits that technological advancements should have a positive impact on people's lives by developing solutions that work well within the local context, rather than simply copying and pasting technology from other contexts, such as from developed to developing countries. Indeed, the DSR method is used to design digital artifact solutions that interact with the problem context and facilitate the development of an effective and efficient information system [66,67]. Osei-Bryson [68] ascertained that DSR focuses both on relevance and rigor; the relevance aspect relates to addressing significant societal problems that involve one or more of the dimensions of development and rigor involve the rigorousness of the process for creating novel purposeful artifact(s) and associated theoretical and practical contributions to the body of knowledge, particularly concerning ICT4D. Therefore, DSR provides insight into what it takes to design ICTs for development that address actual problems. Contrary to Behavioral Science Research (BSR), which strives to develop and verify theories that describe or predict human or organizational behavior, DSR extends beyond human and organizational issues by creating new and innovative artifacts [67,68].

We customized a DSR method and adopted basic elements of the participatory system design methodologies, which involve users actively engaged in the design, testing, implementation, and assessment of the system [59]. We customized the DSR method process by Peffers et al. [69] from six to eight steps: problem identification, requirements, preliminary artifact design, user survey, refined artifact design, implementation, evaluation, and communication. According to the DSR method, problem identification comes first, allowing subsequent processes to focus on developing the artifact solution. The problem identification can emerge from the existing literature (problem-oriented initiation), the users' needs (context/user initiation), or from a desire to achieve a particular objective (objective-centered solution) [69,70]. The second step is to collect the requirements or define the objectives necessary for solving the identified problem. A third step involves designing preliminary artifacts based on the requirements from the previous step. The fourth step is conducting a user survey, which consists of orienting potential users with solution design and understanding user context related to the problem, thereby getting valuable feedback to improve the initial design, leading to a participatory design [71].

Since this study is a problem-oriented initiation, we added a 'user survey' step between artifact design and implementation to get the stakeholders' feedback (user or context initiation) for possible improvements of the original artifact design for an effective and efficient information system. The fifth step is to refine the artifact design based on the identified needs and opinions of the stakeholders. The sixth step provides a proof of concept, which involves presenting and demonstrating a part or all of the artifact solution to potential users. This step is crucial for artifact development; designers and developers can leverage user feedback to improve the design through an iterative process. The seventh step involves evaluating the implementation of an artifact solution to a problem, which consists of monitoring the effectiveness and efficiency of the system. This allows feedback to be used in iterating back to the system design. The eighth step is communication, documenting the system through scholarly and professional publications [69]. Figure 4 illustrates the instantiation of the DSR for our research, with the seventh step revisiting all previous steps to enable an empirical refinement approach in the design of the artifact solution.

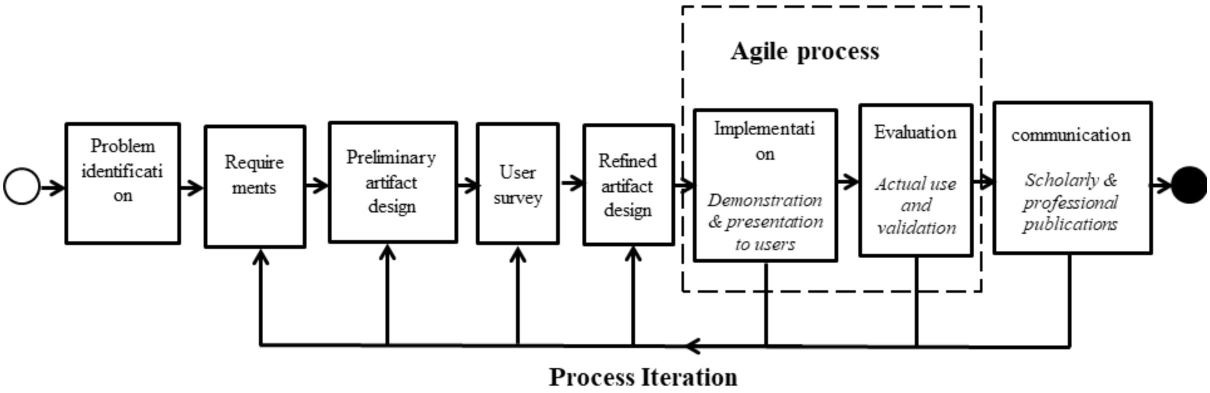

Figure 4. A DSR method used in this thesis [66]

Heeks [72] argued that IT development can be seen as a socio-technical system where IT and society interact by shaping each other. In addition to the survey (the fourth step), which provides stakeholders (the society) with an opportunity to participate in the design of the artifact, the agile methodology enables stakeholders to intervene in the system's redesign during its development. The agile method starts with the planning and development phases, with short spans of iterative and incremental interactions of stakeholders over the process and tools throughout the project's life cycle [73]. This practice enables changes to be made during development without jeopardizing the process or requiring a restart from scratch.

3.3 Other Methodologies

This thesis used different methods at different stages of the DSR methodology to achieve specific objectives. Phase one of the DSR aims to identify the problem and develop requirements for system design. This is linked to Thesis Objective One **(TO1):** to identify common challenges faced by smallholder farmers and the services required for a complete farming cycle. We first identified the problem from the existing literature (problem-oriented-initiation) using PRISMA guidelines. We established system requirements and developed a preliminary artifact design based on the common challenges faced by smallholder farmers identified in the literature. We then conducted a user survey to orient key stakeholders on the designed solution and collect their feedback (user-oriented initiation) towards a concrete system design. This is directly related to Thesis Objective Two: to design and implement a digital platform that addresses the challenges faced by smallholder farmers in Tanzania **(TO2)**. Moreover, the user survey validated the applicability of the designed digital solution **(TO3)**. It provided insight into the prerequisite infrastructures and other capabilities and resources necessary for a framework to be successfully implemented and sustainably operated **(TO4).**

3.3.1 PRISMA Guidelines

We used PRISMA guidelines in this thesis [74], which is a standard protocol and an evidence-based framework for doing systematic review studies. We conducted an extensive literature search based on a complex query in the Web of Science (WoS), IEEE Xplore, and related databases (Food and Agriculture Organization, Google Scholar, and Research4Life). The aim was to find and review the latest literature in digital technology and sustainable agriculture to smallholder farmers. The researchers combined the following keywords using the Boolean operators ("AND" and "OR") and parentheses during the search: digital technology, ICT services, smart farming, precision agriculture, digital farmer profiling, smallholder farmers, and sustainable agriculture. The final search string was "('digital technology' OR 'ICT services' OR 'precision agriculture' OR 'smart farming' OR 'digital farmer profiling') AND 'sustainable agriculture' AND 'smallholder farmers'". However, the search string could not yield satisfactory results from the FAO database due to type and functional differences. We searched in October and November 2021, obtained, and imported a total of 1,981 articles into Mendeley Desktop reference manager software (https://www.mendeley.com, accessed on 4 October 2021).

We applied exclusion criteria to the obtained results to identify relevant papers in digital technology, smallholder farmers, and sustainable agriculture. We restricted the obtained results to the years 2015-2021 to get the latest articles in the subject area. We filtered out duplicate papers (using the duplicate function in Mendeley software), articles without full text, and those not written in English. The inclusion criteria were as follows: (i) modern digital technologies in agriculture (e.g., smart farming, digital farmer services), including the sustainability components (economic, environmental, and social sustainability of the ICT infrastructure and resources); and (ii) the availability of the technology to smallholder farmers. Finally, we selected a total of 36 articles: 24 articles on global literature (21 focused on recent digital technologies and sustainable agriculture, and three on general digital service platforms developed for smallholder farmers), and 12 for the Tanzanian case.

We separately searched the literature in the Tanzanian case in local repositories (Sokoine University of Agriculture Institutional Repository), WoS, and Google Scholar. In this search, we did not limit the literature by year of publication to obtain more detailed background information on the country's ICTs and services for smallholder farmers. We received 18 articles from local repositories for analysis as a result of the complex query "digital technology" OR "ICT services" AND "smallholder farmers" OR "agriculture" AND "Tanzania". We selected 12 articles for review after filtering out five articles that were similar to those found in Google Scholar and WoS (See Table 2).

Table 2. Reviewed literature under the PRISMA guideline.

Search Category	Identification		Screening		Included
General literature	Records identified from databases (N = 1981)	Duplicate removed (N = 85)	Records screened (N = 1687)	Records excluded (N = 1581)	Studies included in the review (N = 24)
		Removed for other reasons (N = 209)	Reports sought for retrieval (N = 106)	Reports not retrieved (N = 11)	
			Reports assessed for eligibility (N = 95)	Reports excluded by the study criteria (N = 71)	
Tanzanian case	Records identified from databases (N = 18)	Duplicate removed (N = 5)	Records screened (N = 13)	Records excluded (N = 1)	Studies included in the review (N = 12)
		Removed for other reasons (N = 0)	Reports sought for retrieval (N = 12)	Reports not retrieved (N = 0)	
			Reports were assessed for eligibility. (N = 12)	Reports excluded by the study criteria (N = 0)	

Source: Mushi et al., [6]

3.3.2 Survey Methodology

We employed a qualitative research approach and case study design to explore the opinions of agricultural stakeholders regarding the designed FDIS, which aims to address common challenges across the entire farming cycle for sustainable agriculture. The study's approach provided an insight into the challenges faced by the agricultural sector, introduced the design of the FDIS, and explained how the envisaged platform will improve agrarian activities. More details on the survey's findings are presented in Chapter 4.

3.4 SWOT Analysis

SWOT is an acronym for Strength, Weakness, Opportunity, and Threats, a model used to identify internal and external factors that affect the business process or methodology performance[75]. This thesis highlights the strengths of SWOT analysis in terms of its internal capabilities for achieving the objectives. Weaknesses are internal factors that may hinder the method's full potential. Opportunities in SWOT analysis for this thesis include factors that can positively influence the performance of the methodology. Threats are negative features that can hinder or delay the achievement of goals. We analyzed various elements to provide a balanced perspective on the DSR methodology employed in this thesis. Table 2 provides an overview of the SWOT analysis of the methodology.

This thesis employed the DSR method, which is both relevant (addressing critical societal problems through various development dimensions) and rigorous (involving the thorough process of creating novel, purposeful artifacts and associated theoretical and practical contributions to the body of knowledge). The DSR facilitates the design and implementation of the FDIS, which enables smallholder farmers and other agricultural stakeholders to access all essential services throughout the complete farming cycle. These include access to financial (insurance and credit), agro-dealers and farm input, subsidies, logistics, warehouse, advisory, government (permit), and market services. The qualitative approach strengthens the research by embracing human factors such as stakeholders' opinions, cultural and environmental aspects, and user behavior, which are critical to the successful implementation of an information system. The thesis focuses on problem-oriented and user approaches that ensure the design and implementation of artifact solutions that interact with the problem context and facilitate the practical application of the solution.

In the weakness, we identified various factors that could hinder the applicability of the study. The designed solution is a data-driven digital platform that raises several data-related issues, including data quality, ownership, sovereignty, and data protection. Therefore, the access of agricultural stakeholders to services depends on the quality of data in the designed FDIS platform. The technical implementation of FDIS under the DSR methodology was conducted for demonstration and presentation purposes. It took the form of a proof of concept, thus lacking evaluation and validation from a real-world implementation. Moreover, the study heavily relies on qualitative approaches, overlooking quantitative elements such as the economic impact of the designed artifact in the agricultural sector, which is crucial in evaluating the production, income, and environmental sustainability factors of the digital platform.

Table 3. SWOT Analysis of Methodology

Strength	• Problem and user-oriented research • Qualitative approach • Address the human factor
Weakness	• Data-driven solution • Lack of quantitative evaluation • Lack of real-world implementation
Opportunities	• Integration with existing systems • Multidisciplinary project • Innovation in sustainable agriculture
Threats	• Data-related issues • Technological failure • Limited ICT infrastructure

Source: Author compilation

In the opportunities part, the digital artifact designed under the DSR method has the potential to integrate with existing systems, particularly through the application programming interface (API). For instance, FDIS could retrieve personal data from the national identity system during registration or other relevant agricultural databases in the country to ensure consistency, data accuracy, and quality. Realizing the full potential of the designed artifact requires a multidisciplinary collaboration of experts from different subjects, such as technology, socio-economic, and environmental. Such collaboration is crucial for implementing an effective and efficient system. The DSR method used in this thesis creates opportunities for the development of innovative digital solutions in sustainable agriculture.

Several threats pose potential risks that could hinder or delay the attainment of the objective of this thesis. The designed digital artifact is data-driven, which raises concerns about data management issues such as data privacy, data ownership, data sovereignty, and protection. It creates the challenge of maintaining a balance between innovative research and adhering to ethical standards and legal requirements for data sharing during service exchange. The outcome of this thesis is technology dependency, which attracts potential risks associated with digital platforms, including technology obsolescence, interoperability issues, and the resources required for continuous maintenance. The outcome of the thesis is designed for low- and middle-income countries, which are mostly lagging in ICT infrastructure development. Moreover, the research outcome targets many smallholder farmers living in rural areas, who are challenged by limited connectivity and power supply.

In summary, this chapter outlines the methodologies employed to achieve the objectives of this thesis. We used the DSR methodology to identify common challenges faced by smallholder farmers, designed and provided a proof of concept of a digital platform called FDIS. We determined its applicability and the prerequisites for successful implementation in sustainable agriculture. Chapters 4, 5, 6, and 7 present the findings and discussions, which provide more details for each thesis objective.

Chapter 4

Surveying Agricultural Stakeholders in Tanzania: What We Learned

4.1 Introduction

This thesis employed a survey method to gather opinions from agricultural stakeholders in Tanzania, validating the common challenges of smallholder farmers identified in the literature and collecting feedback on the FDIS abstract design. We conducted interviews and collected data between January and April 2023.

We conducted interviews to 74 agricultural stakeholders: two (2) heads of divisions and one (1) head of unit at the Ministry of Agriculture (MoA), three (3) agricultural insurance companies, six (6) agriculture credit service providers (financial institutions), 20 cereal crops farmers (maize, wheat and paddy), 12 livestock keepers (cattle and goats), nine (9) agro-dealers, 12 extension workers, and nine (9) customers (processing industries and consumers). We selected stakeholders from 13 regions in Tanzania: Rukwa, Mbeya, Morogoro, Ruvuma, Iringa, Tanga, Manyara, Mjini Magharibi, Kaskazini Pemba, and Kusini Pemba (regions with high production of cereal crops and livestock), Dar es Salaam, Arusha, and Dodoma (major consumers and processing industries). We used purposive sampling to select participants with information relevant to the study [76]. Purposive sampling was used to select participants from the MoA, agricultural credit and insurance services companies, extension workers, and processing industries. A simple random sampling technique was used to choose crop farmers, livestock keepers, agro-dealers, and customers.

The study areas (regions, districts, and wards) were selected based on the criterion of higher production among the three major cereal crops: maize, wheat, and paddy (see Figure 5). The study focused on access to digital services among smallholder farmers in rural and semi-urban areas. Indeed, we collected essential data to understand the status of e-government agricultural services, aiming to empower farmers and address the challenges faced by all stakeholders involved. Figure 5 below shows the sites visited as part of this study.

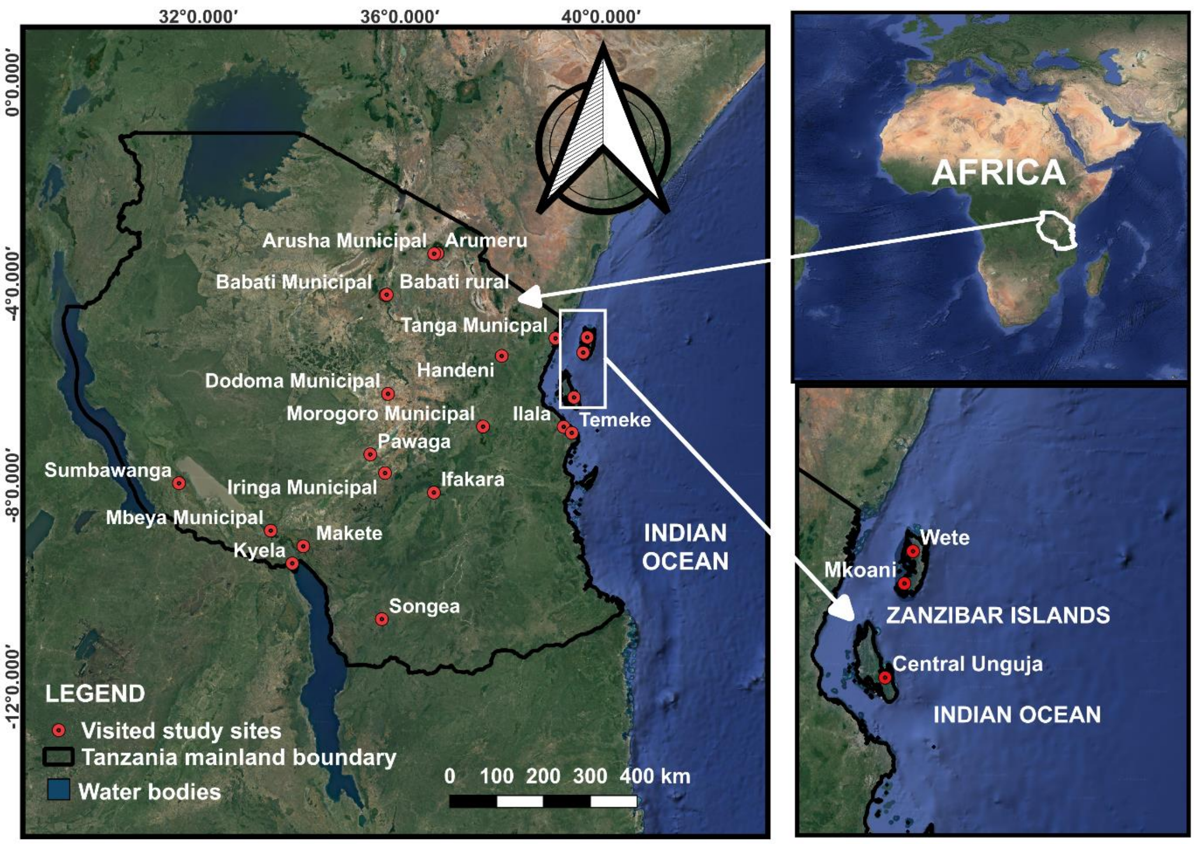

Figure 5. Map of Tanzania showing study districts and sample distributions[64].

In-depth semi-structured interviews enabled participants to explain in detail current practices, challenges, and how FDIS intervention could make agriculture more dynamic. We took note to record the conversations and read the answers provided to the participants for review at the end of the conversation, to ensure the reliability of the data. We then analyzed the data using thematic data analysis [77]. Coded the transcripts and established different categories and subcategories (selected based on stakeholders' raised opinions) represented in the data. Therefore, we have identified themes that span the data categories and reflect the key issues emerging from the data. We extracted and included direct quotes from the participants to highlight key points of the study objectives.

4.2 Findings

We present the study findings under the following themes: stakeholders' current practices, challenges, and opinions on the FDIS design intervention, as well as the capabilities and infrastructure required for FDIS operations. We conducted a comparative analysis among various variables. We assigned codes to the participants as follows: A series (A1, A2...) for agro-dealers, F series (F1, F2...) for crops farmers, L series (L1, L2...) for livestock keepers, C series (C1, C2...) for credit service providers, E series (E1, E2...) for extension workers, CS series (CS1, CS2...) for customers, and AI series (AI_1, AI_2...) for agricultural insurance service providers, while [...] stands for skipped words in the direct quotes.

4.2.1 Stakeholders' current practices, challenges, and opinions on the FDIS design

The study examined the practices, challenges, and views of all stakeholders regarding the design of FDIS as an intervention in Tanzania's agricultural value chain.

Agro-dealers

Agro-dealers are critical stakeholders in agriculture as they determine the distribution, access, and use of quality farm inputs and equipment. The availability of substandard farm inputs, which are harmful to the environment and people's health, underscores the need for registered agro-dealers to have access to information on authorized and banned inputs from the responsible authorities. However, the findings indicate that agro-dealers do not have access to information from the authorities, but rather take other measures, such as buying inputs from reputable manufacturers and importers, and sharing information with other agro-dealers. Agro-dealers have indicated that the obstacle to accessing information is a lack of knowledge of the source and difficulty in gaining access to the responsible authorities. All agro-dealers admitted that their services were focused on urban areas for commercial reasons, which partly explains why most smallholder farmers in rural areas do not have access to, or use, modern farm inputs and equipment.

> "[...] as an agro-dealer, you can't invest in remote areas where the market is smaller. In urban areas, you can sell to many farmers coming from all directions throughout the year, while in rural areas, the sales will be seasonal" (A5, Mbeya).

Table 4 presents a summary of the challenges and opinions of agro-dealers regarding the envisaged platform.

Table 4. A summary of agro-dealers' challenges and opinions on FDIS design

Challenges	Opinions on FDIS design	Refining the FDIS design
Poor access to information from the agro-inputs standards regulatory authorities	FDIS is a link to sources of input information from the authorities, and could help prevent the sale of unregistered and banned inputs	A5, Mbeya proposed the logistics services to solve the challenge of input transportation.
Availability of unregistered agro-dealers	Digitizing the supply of agro-inputs cannot automatically eliminate unregistered agro-dealers	
Low farmers´ purchasing power in rural areas	The ability to make online payments provides the opportunity for input delivery services in rural areas.	

Challenges	Opinions on FDIS design	Refining the FDIS design
Most farmers are aging out.	FDIS can help agro-dealers provide precise inputs and advisory services	
Low literacy to adopt modern farming techniques		
Poor logistics services in agro-input supply		

Source: Field Data

While a few agro-dealers couldn't foresee the challenges of the envisaged platform, most identified illiteracy and poor digital skills as the significant anticipated barriers. Other possible barriers mentioned include the rejection of technology, with many smallholder farmers being too old to accept, learn, and utilize digital technologies. The assertion that most farmers are too old is supported by the demographics of this study (Table 5). The results show that 38% and 41% of the smallholder farmers surveyed are aged 50 and 60 years, respectively. Agro-dealers have indicated that they have digital literacy skills and own digital devices, so they will only need training on the envisaged platform. Agro-dealers have been asked to modify the design of FDIS by deleting or adding certain functionalities that will solve their current problems. They suggested that FDIS should include additional functionality for the transport services provided by logistics companies. The aim is to resolve the current difficulties associated with finding transport services for inputs from manufacturers or importers to different parts of the country. For example, an agro-dealer involved in distributing government subsidies for fertilizers reported spending more than 2 weeks searching for transport services between the manufacturer in Dar es Salaam and the Mbeya region. Apart from modifying the design of the FDIS, agro-dealers suggested improving rural infrastructure, such as a reliable road network and telecommunication, following the example of the rural electrification project currently underway in the country.

Farmers

Farmers play a central role in the agricultural value chain, as they produce food and raw materials, and consume farm inputs and other services, such as credit and insurance, necessary for production. This study investigated both crop farmers and livestock keepers by selecting three major cereal crops (maize, paddy, and wheat) and three primary livestock (dairy cattle, indigenous cattle, and goats) in Tanzania (see Table 5). The survey primarily examined their current practices and challenges throughout the farming cycle, as well as their views on FDIS intervention to enhance their practices, increase production, income, and environmental protection.

Table 5. Demographic characteristics of farmers (N=34)

Variable	**Category**	**Frequency (N)**	**(%)**
Location (Regions)	Tanga	5	14
	Morogoro	2	6
	Mbeya	4	12
	Manyara	5	14
	Iringa	3	9
	Ruvuma	2	6
	Rukwa	4	12
	Kusini Pemba	2	6
	Kaskazini Pemba	2	6
	Mjini Magharibi	2	6
	Arusha	3	9
Location status (Ward level)	Rural	24	70
	Semi-urban	7	21
	Urban	3	9
Gender	Male	25	74
	Female	9	26
Age group (Years)	21-30	3	9
	31-40	4	12
	41-50	13	38
	51-60	11	32
	61 and above	3	9
Educational level	No formal education	2	6
	Primary education	25	73
	Secondary education	6	18
	Diploma	1	3
Farming activity (Occupation)	Maize farming	9	26
	Rice (paddy) farming	8	24
	Wheat farming	5	14
	Dairy cattle keeping	7	21
	Indigenous cattle keeping	4	12
	Goats keeping	1	3
Farm size	Below 3 hectares	1	5
	4 – 6 hectares	14	64
	7 – 9 hectares	7	31
	Below five livestock	2	17
	6 – 10 livestock	7	58
	11 – 15 livestock	1	8
	16 and above livestock	2	17

Source: Field Data

The majority of farmers rely on experience inherited from their parents, the community, and other farmers in most of their activities. For instance, farmers reported using simple tools, such as hand hoes, for land preparation, but a few also reported using tractors and other basic machinery. Crop farmers reported a lack of soil health testing and expert advice on land preparation. Similarly, livestock farmers reported a lack of knowledge and resources for preparing modern animal shelters and selecting quality breeds for production. Although many farmers (31, 91%) indicated that they did not have the necessary services to prepare their farms, a few (3, 9%) reported receiving regular training from non-governmental organizations (NGOs). In other places, manufacturers of inputs, particularly fertilizers and seeds, have been involved in training farmers through model farms.

The results reveal that 23 (68%) of the crop farmers use local seeds selected from previous harvests, and 7 (19%) use quality seeds. In comparison, 4 (13%) use a combination of both local seeds and quality seeds purchased from agro-dealers. Although local or informal seed systems comply with agroecology principles, studies show that they are subjected to low quality and production compared to quality-certified formal seeds [78,79]. Farmers cited the lack of investment capital as a barrier to increasing production, specifically in purchasing and applying modern inputs. On the other hand, dairy livestock keepers indicated that the lack of knowledge and the absence of reliable sources of dairy cattle breeds force them to use breeds available from other farmers on the advice of their fellow farmers. Dairy cattle breeders claim that the available breeds are not pure and that their yields are lower than expected. Moreover, farmers identified other difficulties linked to farm preparation, access to quality inputs, and production management. These include remoteness of agro-dealers, the high cost of inputs, substandard seeds, and, particularly for wheat growers, the latter.

This study collected farmers' opinions on the design of the FDIS intervention throughout an entire farming cycle (see Table 6). Most farmers (30, 88%) indicated that they would agree to use FDIS – the platform that will collect and enable farmers to share their data with other stakeholders to obtain services. Farmers mentioned that the FDIS platform will provide access to essential services from different stakeholders, from the early stages of farm preparation to post-harvest activities. However, 4 (12%) farmers rejected the idea of digitizing the agricultural value chain as conceived by FDIS. Overall, farmers believe that the envisaged FDIS platform will have a considerable impact and change their current practices to increase production and income.

Table 6. A summary of farmers' challenges and opinions on FDIS design

Challenges	**Opinions on FDIS design**	**Refining the FDIS design**
Lack of modern farming knowledge and use of simple farm tools	FDIS could add value to their understanding and improve or change practices in farm production	Information about warehouse services for storing farm harvests.
Farmers do not have access to agricultural insurance and credit services	FDIS could link farmers to insurance and credit service providers for access to sufficient investment capital and develop their farms to increase production and income	Logistics services to solve the challenge of transporting farm products.
Use of low-quality farm inputs such as seeds and fertilizer		Ability to request different permits from the authorities. Example:

Challenges	Opinions on FDIS design	Refining the FDIS design
Crop farmers depend on rainfall for irrigation while using experience to predict the rain season.	FDIS will help provide access to reliable weather information for precise rainfall forecasting, reducing the risk of crop loss due to droughts or floods.	harvesting permit and farm products transportation or exportation permit.
Smallholder farmers depend on intermediaries (middlemen) to sell their produce. This system is exploitative for farmers, as it forces them to accept lower prices for their farm products.	Farmers indicated that FDIS could be a source of market information and a platform for marketing their products. Thus, it could help eliminate the middlemen in the value chain as farmers could directly meet the potential buyers and sell at a better price.	
Substandard inputs in the market result in poor production	Farmers could identify certified agro-dealers and verify the authenticity of farm inputs.	

Source: Field Data

Credit services providers

Financial institutions are essential stakeholders in the agricultural value chain, as they provide credit services to other stakeholders for investment purposes. This study investigated current interactions and challenges between financial institutions and smallholder farmers. The study introduced FDIS to credit service providers and collected their views on improving credit services to smallholder farmers. We interviewed six commercial banks located in different regions of agricultural production. However, only one community bank was physically operating in rural areas; the others were in urban areas. Four credit service providers indicated that they granted loans in cash and farm implements, while two revealed that they only granted cash loans.

The findings reveal that financial institutions provide credit services to farmers, but these services are subject to a series of conditions for smallholder farmers. For example, one of the financial institutions mentioned that it would only provide credit services to farmers who use an irrigation system and whose crops have a stable market, thereby avoiding the risk of loan default. The study also revealed that financial institutions grant personal loans to large and medium-sized farmers. In contrast, smallholder farmers are often compelled to form farmers' groups or associations to access credit services.

> "The large and medium-sized are eligible for personal loans, but smallholder farmers must organize themselves in groups to achieve collective responsibility in loan recovery, thus avoiding risks" (C6, Ruvuma).

Financial institutions indicated that the rate of smallholder farmers' access to credit services is generally low, and the majority have no access to this service in the country.

The study of the conditions for applying credit services to farmers revealed that the information and documents required are personal information with identities, land documents and ownership status, the farm business plan (types of crops, irrigation condition, etc.), or other asserts held by the farmer and documents, loan history and farm production and sales records. For farmers' groups or associations, the conditions are the affirmation of group members and operating contracts (in case of contract farming). The findings also reveal that many credit service providers require collateral such as land and property titles and vehicle registration documents. However, one of the financial institutions indicated that requiring collateral is not always the case for smallholder farmers.

> [...] "We consider the good crop structure with a well-defined value chain, particularly contract farming. We have issued around 7.8 billion Tanzanian shillings to farmers without any collateral. On the other hand, farm tools loaned to farmers are used as collateral" (C4, Dar es Salaam).

However, the study found that not only has contract farming improved lending conditions for smallholder farmers, but so have guarantors such as Tanzania Agricultural Development Bank (TADB), which guarantees farmers up to 50% of their income. Meanwhile, in other parts of the country, the farm itself stands as collateral due to its high value; thus, smallholders do not need to submit other assets. The findings show that many financial institutions cited the demand for collateral as a barrier for most smallholder farmers who cannot meet the loan eligibility criteria. Some credit service providers mentioned that smallholder farmers lack education about loans, as well as poor knowledge of loan conditions, such as the strict conditions for improvement.

> [...] "Many farmers are not aware of the loan education; they don't know that even without a house or land title deeds, one can get credit service. Indeed, commercial banks are agencies of the Tanzania Agricultural Development Bank, which provides a 50% guarantee, and the farmers bear the remaining 50%. Still, we may cover up to 75% loan guarantee to other farmers, thus they don't need strong conditions to cover the remaining 25%" (C6, Ruvuma).

Other barriers to smallholder farmers' access to credit services are mentioned, including weak credit services in rural areas, refusal of service due to high production risks, such as dependence on seasonal rainfall, and poor market conditions for specific crops.

Focusing on the challenges of financial institutions' relations with smallholder farmers, the findings reveal that credit service providers have many times struggled to recover loans after smallholder farmers failed to repay. The mentioned reasons for the failure are the mismanagement of loans based on the farm business plan, particularly using loans for purposes other than agricultural ones. However, other farmers are unable to repay for valid reasons, such as poor market conditions for their crops and production losses due to floods, drought, pests, and disease. The study shows that smallholder farmers have a “bad character” because they hide essential information or cheat financial institutions when assessing a loan. For instance, if a farmer presents someone else’s land ownership documents as his own when applying for a loan, the financial institution will notice this when it comes to loan collection problems. One of the financial institutions indicated that some of the challenges, such as farmers' use of loans for purposes other than intended and failure to repay, might have been caused by credit service providers, as they take a long time to process loans for farmers. For example, a farmer receives a loan after important early-stage activities, such as land preparation and planting, have already been completed, so the loan will not be used as intended. Financial institutions have identified other challenges to the provision of credit services to smallholder farmers in Tanzania: few institutions provide financial services to farmers under rigid conditions, loan processing costs are high, the agriculture sector is neither formalized and nor dynamic, and the majority of smallholder farmers lack collateral and are not involved in a well-structured crops value chain.

The findings reveal that financial institutions are open to the idea of the FDIS, with opinions that the envisaged platform will address many of the challenges in providing credit services to smallholder farmers. Financial institutions' managers claimed that the comprehensive farmer data contained in the envisaged platform is essential for minimizing the risks involved in lending to smallholder farmers. It will also help financial institutions process and grant loans promptly as soon as the data becomes available. The findings show that the managers of three financial institutions indicated that it is not currently possible to receive applications and grant loans entirely online on the FDIS platform. In contrast, two stated that it is possible, and one mentioned that the first loan application should be face-to-face, with subsequent applications able to be made entirely online. When asked whether financial institutions' access to farmers’ comprehensive data in the FDIS could replace the demand for collateral, enabling many farmers to access credit services, four institution managers indicated that data could not replace the demand for collateral. At the same time, two mentioned that access to data could influence the assessment of farmers using criteria other than collateral, such as house titles.

> “The issue is not access to data; humans are subjected to 'character change ', thus collateral is the last resort. Data is used to issue loans while collateral is useful for loan recovery” (C5, Iringa).

While many financial institutions' managers indicated that access to data alone cannot replace requests for collateral, one financial institution manager mentioned that a well-structured crop value chain, particularly under “contract farming”, is enough to issue credit services to smallholder farmers without demanding collateral. The findings reveal that financial institutions believe the FDIS could be beneficial to their institutions and help eliminate many challenges to smallholder farmers' access to credit services. They pointed out that access to data from other stakeholders, such as processing industries and agro-dealers, on the FDIS platform could make the agriculture sector more dynamic, as they already have established good business relations. The identified anticipated challenges of the envisaged system by financial institutions include network problems, which they face even in the current banking system; cybersecurity issues; a lack of cooperation from other key stakeholders; and the quality of data. The study found that the identified major strength of the FDIS platform is the collection of comprehensive data on farmers and other stakeholders, which can be shared to access services, and could also help better formalize the agricultural sector. In modifying the design of the FDIS, financial institutions suggested that the envisaged system record the history of loans granted to farmers, add essential stakeholders such as TADB, and implement a scorecard system that shows the likelihood of farmers receiving credit services based on the quality of data entered into the platform.

Customers

Customers play a key role in the agriculture value chain, as they determine the market and the income of farmers and other stakeholders. In this study, customers refer to the processing industries that purchase agricultural products from farmers as raw materials, as well as domestic customers who buy agricultural products directly from farmers for consumption. We interviewed a total of nine customers, four managers from the processing industries, and five domestic customers in various regions of Tanzania.

The findings reveal that customers collectively could accept the FDIS design and would use the envisaged platform to buy directly from farmers. Customers believe that buying directly from farmers through the FDIS will add significant value to all parties. One of the processing industry managers mentioned that FDIS will help processing industries obtain information from farmers, such as crop products, location, price, and quantity of farm products, at the right time and at a reasonable cost. Moreover, customers believe that FDIS will reduce the cost of acquiring farm products while increasing farmers' income through better prices compared to the existing value chain, which involves intermediaries. All the interviewed customers believe that FDIS will promote agricultural development in several ways, including eliminating middlemen in the value chain, increasing farmers' incomes, encouraging investment and production on farms, and reducing the cost of production for processing industries and, ultimately, for end consumers. In addition, the planned platform will provide an essential link between farmers and processing industries:

> [...] The platform serves as a bridge between farmers and other stakeholders. The stakeholders' network has the following advantages. 1) Processing industries can directly communicate with farmers on the standards required for production, unlike the current situation, where farmers produce at standards not needed by the industries or the market. 2) The linkage can also inform farmers of types of crops they should grow based on the market needs" (CS_1, Arusha).

Moreover, the findings indicate that customers collectively hold the opinion that eliminating intermediaries in the agricultural value chain by purchasing directly from farmers through FDIS will reduce the price of farm commodities as raw materials and stabilize market prices for farm products. The findings identified bank transfers and mobile money as the preferred methods of payment for customers to make transactions with farmers on the envisaged digital platform. Investigating the anticipated challenges to the envisaged platform, the findings reveal that customers mentioned infrastructure issues, particularly Internet service in rural areas, poor digital literacy, with the majority of farmers being too old, and the costs of the Internet bandwidth.

Agricultural insurance services

This study interviewed three directors of the agricultural insurance service providers: two of them offer insurance for both crops and livestock, and the third offers only crop insurance. The directors of the insurance service companies have indicated that they provide services to individual farmers or groups of farmers. The findings reveal that insurance services are crucial for covering the various risks associated with agricultural production. Identified risks covered by agrarian insurance companies include climatic risks such as floods, droughts, and hail; the vegetation index; pests and diseases; theft; and fire outbreaks. The covered risks in livestock production are sudden death, forced slaughter, and diseases beyond the farmer's control. On the other hand, the findings show that insurance service providers offer different packages to their clients. One of them offers two main packages: input coverage, which only covers the cost of inputs, and production coverage, also known as area index, which is a comprehensive insurance policy covering all production risks. Another insurance company offered four different packages: the Meteorological Index, which covers weather-related risks; the Soil Moisture Index; the Surface Yield Index; and the Multi-Risk Crop Insurance, which covers all risks related to farm production.

Moreover, the study findings reveal that the surface index cover is the most widely purchased agricultural insurance from all service providers.

Insurance service providers collectively believed that farmers' access to insurance services was limited due to a lack of awareness and low income. Insurance companies provided an estimated number of active agricultural insurance subscribers, as shown in Table 7.

Table 7. Agricultural insurance subscribers

Insurance company code	**Years of experience**	**Estimated active subscribers in Tanzania**
AI_1	9	40,000
AI_2	8	30,000
AI_3	11	26,000

Source: Field Data

The study revealed that insurance companies collect information on agricultural production through a survey form that gathers details on the farmer, production and loss history, farm size, location, and crop types. Other insurance company works with extension officers to collect this information and farmers' yield expectations. We also found that insurance companies work closely with weather and agricultural data companies, particularly "ACRE Africa," to get the weather index information for evaluation of related risks in different locations. Therefore, insurance service providers visit the farm or livestock to identify potential hazards and advise the farmer on the appropriate insurance package. The findings show that all insurance service providers have had the experience of compensating farmers who have lost production due to climatic hazards (drought, floods, and hail) and farm invasions by wild animals. Further findings on the current challenges and opinions on the FDIS design are presented in Table 8 below.

Table 8. A summary of insurance service providers' challenges and opinions on FDIS design

Challenges	**Opinions on FDIS design**	**Refining the FDIS design**
Farmers' low awareness and lack of education about agricultural insurance result in low utilization of the service.	The availability of all services on one platform (FDIS) could increase farmers' awareness and utilization of insurance services.	FDIS should link the farmers' insurance subscription information between companies to avoid fraud and duplication.
Lack of agricultural data	FDIS could fill data gaps, which are essential for providing services to farmers	FDIS should integrate essential stakeholders, such as the "ACRE Africa" company, which provides agricultural and weather data
High risk of fraud		
High cost of operation and low purchasing power of farmers	FDIS bridging the existing data gaps could influence the design of new affordable insurance packages or provide customizable packages to farmers.	

Challenges	Opinions on FDIS design	Refining the FDIS design
Lack of government support, such as insurance subsidies, makes the service compulsory for farmers.		
Lack of agricultural insurance experts (no formal training is offered in the country)		

Source: Field Data

Indeed, insurance service providers have determined that the envisioned FDIS platform has the potential to alleviate most of the challenges faced by smallholder farmers in accessing insurance services. However, it will require the cooperation of other stakeholders, such as financial institutions and government agencies. Moreover, agriculture insurance should be included in the higher education curriculum to produce experts in this sector. Insurance service providers mentioned having relationships with other stakeholders, such as agro-dealers, processing, and farm input industries, which reinforces the idea that FDIS could extend its services to help smallholder farmers become part of this agricultural stakeholder ecosystem and make the agriculture sector more dynamic. However, insurance providers anticipate that using the envisaged platform will incur new charges, which could increase the costs of operation and technical infrastructure.

Extension workers

Extension workers are key stakeholders in the Tanzanian agricultural system because they disseminate agricultural advisory services and expertise, and implement government policies and actions to improve the sector's production and product quality. In this study, extension workers refer to agriculture experts employed by the government to work closely with farmers, offering their expertise and advisory services to crop farmers and livestock keepers. The interviewed extension workers in different parts of Tanzania had varied experiences, with some offering expertise exclusively in crop farming or livestock keeping. In contrast, others provided both (see Table 9 below for more details).

Table 9. Demographic data of extension workers (N=12)

Variable	Category	Frequency (N)	(%)
Location (District, Region)	Handeni, Tanga	1	8.3
	Ifakara, Morogoro	1	8.3
	Mbeya council, Mbeya	1	8.3
	Babati, Manyara	2	17
	Iringa council, Iringa	1	8.3

Variable	Category	Frequency (N)	(%)
	Songea, Ruvuma	1	8.3
	Mollo, Rukwa	1	8.3
	Ng'ombeni, Kusini Pemba	1	8.3
	Wete, Kaskazini Pemba	1	8.3
	Cheju, Mjini Magharibi	1	8.3
	Arumeru, Arusha	1	8.3
Location status (Ward level)	Rural	8	67
	Semi-urban	4	33
	Urban	0	0
Gender	Male	8	67
	Female	4	33
Age group (Years)	20-29	0	0
	30-39	9	75
	40-49	3	25
	50-59	0	0
Agricultural educational level	Certificate	0	0
	Diploma	12	100
	Bachelor's degree	0	0
Agricultural service category (Occupation)	Crop farming advisory service	3	25
	Livestock management advisory services	4	33
	Both crop farming and livestock management advisory services	5	42
Working experience (Years)	Below 5	1	10
	6 – 10	5	40
	11 – 15	6	50

Source: Field Data

Investigating existing digital means of reaching farmers, the findings reveal that the majority of extension workers have been introduced by chance to "Mobile Kilimo" (M-Kilimo) – a government-owned mobile and web-based application for services to farmers and other stakeholders. However, most of them have not used the application due to a lack of digital devices, the high cost of Internet, and the absence of government support. The other mentioned digital means that extension workers have been using to reach farmers are WhatsApp and standard mobile communication.

> "We were once introduced to M-Kilimo, managed by the Ministry of Agriculture. However, the system failed to function, and I no longer use it. When I send an SMS to farmers, it is not delivered. If it were functioning, I could use it because I had already introduced the system to the very interested farmers, and I enjoyed helping farmers digitally at any time. After it collapsed, I decided to create a WhatsApp group to keep the service alive. But I also use normal SMS and phone calls" (E4, Manyara).

Other findings show that many extension workers are unable to visit and respond to farmers' emergencies due to a lack of transport, which is a significant challenge given that they must serve many households scattered in remote areas. Other challenges include the reluctance of farmers to seek and utilize information and knowledge from experts, as well as livestock farmers who don't allow experts to visit their farms. Table 10 below summarizes the challenges and opinions of the extension workers regarding the FDIS design.

Table 10. A summary of extension workers' challenges and opinions on FDIS design

Challenges	Opinions on FDIS design	Refining the FDIS design
Many farmers per one extension worker (an average ratio of one to two thousand)	The FDIS platform will simplify the farmers' access to extension workers' services in a flexible and timely manner.	FDIS should enable working offline to facilitate extension services in areas with poor infrastructure.
Difficult to provide farm-specific advisory services	Possibility of farm-specific advisory, distance service, and respond to emergencies such as requests for animal treatment, pests, and disease outbreaks, as FDIS could provide access to farm and livestock data.	
Lack of transport in the scattered farming population in rural areas		
Poor motivation due to complex working conditions, such as a lack of digital devices and Internet service		

Source: Field Data

In introducing the FDIS design, the findings reveal that extension workers collectively accepted the idea and could use the envisaged platform. However, extension workers anticipate that farmers' digital illiteracy, poor infrastructure, particularly in rural areas, and the high cost of Internet bandwidth will be significant barriers to the envisaged FDIS platform, in addition to poor working conditions, such as limited access to digital devices. In general, it was stated that having access to extensive data in the proposed system would represent a significant advancement in addressing the challenges encountered when collaborating with farmers and other stakeholders.

Ministry of Agriculture

The Ministry of Agriculture (MoA) in Tanzania plays a central role in developing policies, regulating the manufacture and import of agro-inputs, controlling and monitoring the market for agricultural products, particularly the exportation of food crops, and enabling smallholder farmers to increase production through subsidy programs. Therefore, the MoA coordinates the activities and works with all key stakeholders to promote agricultural development. This study interviewed two heads of division – the Crop Development Division and the Agricultural Training, Extension

Services, and Research Division - and one head of unit – the Information and Communication Technology Unit – within the MoA in Tanzania.

This study ascertained that the MoA has established digital services for farmers to promote sustainable agriculture. Those services are the M-Kilimo application, a call center for extension services, and the DFSDS. Introducing the FDIS design to the MoA reveals that the envisaged platform has complementary features and will solve a broader range of challenges compared to the currently proposed services.

> [...] "Based on your explanation of the FDIS system, we are yet to have a system with all such features, especially bringing together all agriculture stakeholders in the country, but we hope we will improve to reach that level of the envisaged system" (MoA, Dodoma).

On the other hand, the MoA mentioned that the government and its agencies involved in the agriculture sector is ready and willing to adopt any essential new suggestions to improve the existing systems. The MoA emphasized that the envisaged platform could be an opportunity for all agricultural stakeholders in the value chain, as it could enable transparent collaborations and services, rendering the agriculture sector even more dynamic. Table 11 below presents the MoA's ICT-related services to farmers and statistics on usage.

Table 11. Ministry of Agriculture ICT-based services.

Name of the platform	**When launched**	**Registered stakeholders**		**Types of services**	**Usage statistics**
M-Kilimo application	May, 2020	Farmers	7,269,106	Market and price information, selling and buying, advisory services, and feedback	Number of consultations (advisory services) 75,623 Replied to queries 73,839
		Extension workers & experts	9,985		
		Customers	24,523		
		Agricultural products sellers	26,927		
Digital Fertilizer Subsidy Distribution System (DFSDS)	September, 2022	Farmers	2,828,300	Manage the distribution and access of subsidies to farmers	Over 350,000 farmers had received subsidized fertilizer.
		Importers	29		
		Manufacturers	3		
		Agro-dealers	3181		
A Call Center	July, 2022	All agricultural stakeholders are encouraged to submit suggestions, report complaints, request information, or seek professional advice.		Stakeholders can inquire about any aspect of the agricultural sector, such as issues with crops, livestock, fishing, marketing, and agro-inputs.	Total calls: 5202 Calls back: 2301

Source: Field Data

The findings reveal that the government, through the MoA, can adopt and provide all resources required to sustain the envisaged FDIS platform.

> "Since we already have sections dealing with extension services and digital application system in place and functioning, we will be able to adopt and sustain the envisaged system, which looks more of improving the existing systems" (MoA, Dodoma).

The MoA holds the opinion that the FDIS design aligns with the recently launched government project, "Building Better Tomorrow – Youth Initiative for Agribusiness (2022-2030)". Thus, implementing the envisaged platform could attract young workers in the agribusiness by providing them with innovative services that benefit all stakeholders, thereby increasing production and income.

The MoA recommended adding specific features to the FDIS, including transportation services from logistics companies, access to the international market for farmers' and farmers' associations, renting storage space in warehouses, and the ability to request and receive various government permits, such as crop harvesting and exportation permits. The MoA added that the FDIS platform should be able to distribute different types of subsidies, including fertilizers, seeds, implements, and other farm inputs. However, the existing digital services proposed by the MoA face several challenges, which will also be present in the envisaged system: inadequate support and lack of motivation for extension workers, high costs of Internet services, poor infrastructure in some rural areas, and a high level of digital illiteracy.

4.2.2 Summary of the Findings

Indeed, this chapter reveals stakeholders' challenges and readiness of adopting the FDIS design given the envisaged platform has the potential to solve many of their current challenges present in the complete farming cycle and could further motivate farmers and other stakeholders to target a more sustainable agriculture, to increase production and income, and be more respectful to the environment. Table 12 presents a summary of common challenges raised by all agricultural stakeholders.

Table 12. A summary of common challenges raised by the stakeholders.

	Crop farmers	**Livestock keepers**	**Agro-dealers**	**Extension workers**	**Insurance services providers**	**Credit services providers**	**Customers**
Lack of access to credit and insurance services	√	√	×	N/A	N/A	N/A	N/A
Poor transport and logistics services	√	√	√	√	N/A	N/A	√
Poor access to data, advisory, and information services	√	√	√	√	√	√	√
Market dependence on the intermediaries (middlemen)	√	√	×	N/A	×	×	√
Illiteracy and a lack of awareness of different services from other stakeholders	√	√	√	√	√	√	×
Lack of storage and warehouse information services	√	×	√	N/A	N/A	N/A	√
Low-quality farm inputs	√	√	√	N/A	N/A	N/A	N/A

Note: √ = Applicable, × = Not a challenge, N/A = Not Applicable.

Source: Mushi et al., [64]

Chapter 5

The Design of the Farmers' Digital Information System (FDIS)

5.1 Introduction

Digital technologies have the potential to address the challenges faced by smallholder farmers and facilitate their participation in sustainable agriculture. This thesis focused on designing and implementing a digital platform that provides essential services to increase the production and income of the majority of smallholder farmers, primarily in low- and middle-income countries. Smallholder farmers face different challenges at all levels of farming activities. Indeed, identifying the common challenges and services required at each stage of the farming process could help increase smallholder farmers' participation in sustainable agriculture. Therefore, we first identified the common challenges and services needed to facilitate the design and implementation of a digital platform as a solution. Secondly, we have developed a preliminary design that showcases the services the digital platform could provide for smallholders. Thirdly, we presented the initial design to key agricultural stakeholders in Tanzania and used their feedback to develop a concrete design for the FDIS. Lastly, we provided a part of the FDIS platform as a proof of concept and demonstrated various services as a solution to the challenges faced by smallholder farmers.

5.2 Common Challenges and Services Needed by the Smallholder Farmers

We used PRISMA guidance (section 3.3.1) and a user survey (section 3.3.2) to identify common challenges and services from the literature and key stakeholders, respectively. The findings presented the use of digital technologies in the agricultural sector for large-scale, medium-scale, and small-scale farmers in both developed and developing countries, as well as the application of digital technologies in the Tanzanian case. For a long time, the agricultural sector has adopted new technologies to enhance production and profitability while also improving the environment. The OECD defines digital technologies as: “ICTs (information communication technologies), including the Internet, mobile technologies and devices, as well as data analytics used to improve the generation, collection, exchange, aggregation, combination, analysis, access, searchability and presentation of digital content, including for the development of services and apps” [60]. Farmers utilize digital technologies in various agricultural domains (summarized in Table 13). These domains include digital technology for farm management, financial services, market services, and farming knowledge and information services. Additionally, some digital platforms provide all essential services to farmers in the farming ecosystem. Many ICT projects for farmers at the national level offer solutions to a specific farming problem, primarily for a particular value chain.

Table 13. A summary of digital services for farmers.

Services		Digital Artifact Solutions	Sources
Farm management	IoT	Sensors: Fixed position, UAV, Satellites, UGV	[17,18,21,22,24]
	Data Management and Analysis	Farm Management Information Systems (FMIS)	[13,26,27]
	Decision-making and Variable Rate Technology	Variable rate nitrogen fertilizer (VRNF), CLAAS VRT, Automated yield monitoring system II (AYMS II), fuzzy logic DSS, AgroDSS	[28,29,31,33]
Financial services		Index-based agricultural insurance, AFPOH, M-Banking	[42,46–49]
Knowledge and information		Weather forecasts, pesticides, and fertilizer information; KALRO mobile applications, Farmers Advisory Systems	[43,52,80]
Market		eSoko, Tru Trade, E-Wallet Scheme, E-Krishok, and Zero Hunger	[42,54,80,81]
e-government		Online Fertilizer Recommendation System (OFRS) in Bangladesh, AFPOH in India, KALRO in Kenya	[42–44]
Profiling platform		Digital farmer profiling platform	[82–84]

Source: Mushi et al., [66]

5.2.1 Farm Management

The current industry 4.0 digital transformation in agriculture integrates IoT, cyber-physical systems, AI, Big Data, Machine Learning, and Cloud computing with agricultural machinery [85]. It is more common to use precision agriculture, whereby innovative ICT solutions and IoT components, such as sensors, monitor spatial and temporal variability in farm production [13,14]. Site-specific farm management provides an understanding of soil and crop characteristics unique to each field, thus enabling farmers to apply farm inputs (such as irrigation, fertilizers, pesticides, and herbicides) in small portions where needed for the most economical production [15]. Controlled farm inputs increase farm productivity and profitability and conserve the environment, promoting sustainable agriculture development[16]. Precision agriculture and smart farming rely on data management to make valuable decisions. The embedded digital technology components can be categorized into three phases: (1) data collection (IoT), (2) data management and analysis, and (3) decision making and variable rate technology (actuation) [5].

IoT and Data Collection

The IoT in agriculture utilizes sensors and other digital technologies to collect vital field data, enabling efficient crop monitoring and informed decision-making. These sensors may be installed on mobile farming equipment or positioned at fixed locations, such as weather stations.

For example, Kilin [15] implemented a network of automated stations across vineyards to detect pathogen-affected zones, enabling targeted pesticide application. These stations continuously capture real-time metrics, including airborne particles, temperature, air and soil humidity, solar radiation, spores, and leaf moisture. AI then processes the spatial and temporal variation data, using optical particle counters (OPCs), to identify areas compromised by pathogens such as *Plasmopara viticola* [15]. This precision-guided approach promotes cost-effective farming, healthier produce, and environmentally sustainable practices.

Saiz-Rubio [5] categorized sensors into three types: remote sensing, airborne, and proximal sensing. Among these, remote sensing—mainly via satellites—has proven indispensable for collecting agricultural data in smart farming systems. Notable satellite tools include WorldView-2 and WorldView-3, which apply the Normalized Difference Vegetation Index (NDVI) standard for multispectral imaging. Additionally, Europe's Sentinel-2 satellite provides 10-meter resolution imagery in four spectral bands every ten days, while the U.S.-based Landsat satellites offer similar spectral data at intervals ranging from 16 to 18 days [5,19].

Aircraft-based sensing, typically involving remotely piloted aircraft (RPA) or unmanned aerial vehicles (UAVs) like drones, gathers detailed field data from altitudes up to 100 meters—dramatically closer than the 700-kilometer range used in satellite-based sensing [18]. While aircraft sensing demands significant expertise and investment to produce high-quality data, it offers notable flexibility, especially in accessing field zones that are otherwise unreachable by traditional equipment.

Proximal sensing represents the cutting edge in agricultural monitoring, employing autonomous ground systems to observe crops from distances as close as 2 meters [18]. As outlined by Saiz-Rubio [5], this technique involves mounting advanced sensor payloads on ground vehicles that traverse the fields, collecting precise data directly from the plants. This method enables immediate, localized actions, such as targeted fertilization and spot-spraying of herbicides or pesticides when weeds or pests are detected [19].

An exciting extension of proximal sensing is the integration of robotic technologies, particularly unmanned ground vehicles (UGVs), which automate various agricultural tasks, including soil analysis, seeding, transplanting, harvesting, and crop scouting [20]. These robots facilitate continuous data acquisition to track crop development and field conditions [21]. Innovations like VineRobot and Vinescout—projects backed by the European Commission—are transforming vineyard management by mapping canopy features and assessing water and nutrient levels [5].

The agricultural robotics sector is also producing specialized scouting machines. For instance, Rowbot Systems LLC (USA) has developed a multifunctional robotic platform capable of identifying growth zones and applying fertilizer accordingly [22]. Similarly, the Oz robot offers autonomous solutions for weeding and seeding operations [23].

Data Analysis and Management

Digital systems in agriculture leverage data from diverse IoT devices to generate actionable insights that enhance production efficiency. Large-scale and commercial farmers increasingly rely on Farm Management Information Systems (FMIS) to collect, store, analyze, and manipulate data for precision and smart farming. FMIS platforms support comprehensive oversight of farming operations—from initial planning to harvest—while recording key details about each activity performed [24].

These systems enable farmers to access information, such as field maps and crop conditions, empowering them to make informed decisions that reduce resource usage, meet regulatory standards, and maintain high-quality yields. A variety of FMIS solutions are available on the market, most of which are proprietary, offering specialized features for managing farm-generated data. They automate tasks such as planning, monitoring, decision support, and recordkeeping based on the processed information [25].

As noted by Hrustek [11], FMIS can document vital aspects of farming, including "harvests and yields, profits and losses, farm task scheduling, weather prediction, soil nutrient transport, and field mapping." Popular FMIS platforms—primarily developed by companies in industrialized countries—include ADAPT, Agrivi, Agroptima, and Farmleap. Advanced systems take it a step further by offering early warning capabilities, integrated financial management tools, and connectivity with key supply chain actors, including input providers and product distributors.

Decision-Making and Autonomous Execution

Modern agriculture generates vast volumes of data influenced by diverse field parameters, making manual analysis both labor-intensive and prone to errors [11]. To navigate this complexity, farmers are increasingly turning to AI and machine learning to interpret large datasets and support informed decision-making. Hrustek [11] highlighted the growing role of these technologies, while Wolfert [26] emphasized the wide-ranging potential of agriculture for AI applications.

Several innovations illustrate this trend. Giusti and Marsili-Libelli [27] developed a decision support system (DSS) leveraging fuzzy logic to optimize irrigation based on soil properties and crop type. Bazzani [28] introduced another DSS that evaluates water availability—both short- and long-term—according to variables like soil type, machinery, and irrigation infrastructure. Rupnik et al. [29] created AgroDSS, a cloud-based tool that interfaces with farm management systems via an application programming interface (API), enabling outputs for targeted tasks such as pest control.

Autonomous decision-making has become increasingly feasible thanks to variable rate technology (VRT). Hrustek [11] described *actuation* as the execution of field activities following data-driven decisions. VRT uses robotic systems to carry out a range of tasks—from land preparation and planting to fertilization, pest management, and harvesting [16,17]. These devices receive instructions from computerized DSS platforms and execute precise operations, such as applying inputs only in affected field zones or conducting targeted harvests [3].

Examples of VRT machines include the Automated Yield Monitoring System II (AYMS II), which incorporates advanced "eye" color cameras and real-time kinematic GPS for efficient wild blueberry harvesting [82]. Another example is the sensor-based variable rate nitrogen fertilizer (VRNF), which employs multispectral sensors and tractor-mounted spreaders to apply nitrogen exactly where needed, based on crop measurements [31]. The CLAAS VRT system, compatible with ISARIA sensors, similarly applies nitrogen with high precision [11]. By optimizing input use, VRT boosts productivity while supporting environmental sustainability through reduced reliance on fertilizers and chemicals [32].

5.2.2 Financial Services

Smallholder farmers face the challenge of accessing financial services, which affects the agricultural production and income of many rural communities in developing countries [45]. Digital technology is a crucial tool for enhancing access to finance and promoting the commercialization of smallholder agriculture. A study on the awareness and use of m-banking (mobile banking) reveals that most smallholder farmers in Kenya utilize the technology to access finance for agriculture-related activities [46]. Kirui [46] and pesticides, leading to increased production and income. The AFPOH is an ICT-based agriculture initiative in India that enables most smallholder farmers to access finance for improved agriculture [42]. Different countries embrace digital technology to allow the commercialization of smallholder agriculture as poverty alleviation and food security strategy.

Furthermore, agricultural insurance is an essential service for smallholder farmers. The farmers commonly encounter various production and market risks, which lower their income and ability to produce year after year. Hess and Hazell [86] noted that natural disasters, including extreme droughts, floods, hurricanes, and pest outbreaks, are common risks for smallholders. The risks have severe impacts on economic development, leading to extreme poverty. In the past, governments and organizations have developed several insurance programs to assist small farmers in adopting sustainable agricultural practices. However, farm stakeholder and organizations considers index-based agricultural insurance as more effective for smallholder farmers in developing countries [48,49]. Still, the majority of smallholder farmers, particularly in Africa, have no access to insurance. For instance, approximately 650,000 farmers have access to insurance in Africa out of around 40 million smallholder farmers in Sub-Saharan Africa alone [86]. The current trend of climate change requires financial investment for agricultural transformation, including increasing availability and access to credit and insurance by smallholder farmers [50].

5.2.3 Information Services

Effective dissemination of agricultural information and knowledge is key to advancing farming practices. Many smallholder farmers lack access to vital agricultural expertise and instead rely on personal networks or prior experience, often leading to reduced productivity [49]. Providing data throughout every stage of the farming cycle—from land preparation and input selection to financing, harvesting, and product marketing—can significantly enhance the commercial success of smallholder agriculture.

Ali et al. [50] identified the information needs of farmers in Pakistan and developed a digital platform that provides weather updates and guidance on pesticide and fertilizer use. In India, e-agriculture initiatives focus on delivering agricultural knowledge to rural smallholder farmers through ICT tools such as management information systems, expert systems, and knowledge-sharing platforms [40]. Similarly, Sanga et al. [51] developed an information dissemination system that connects smallholder farmers to agricultural experts, using ICT to fill gaps left by limited extension services.

Mobile applications are playing an increasingly important role in spreading crop and livestock information. For example, the KALRO in has launched over fourteen mobile apps to assist farmers with adopting modern techniques and boosting productivity [41].

5.2.4 Market Services

Most large-scale farmers use advanced FMIS, which provides a link to critical services, including the market [54]. For instance, we can mention the combination of different methodologies to design information integration in the Netherlands for information sharing that supports the food supply chain—a movement of food into various stages from farmers to consumers and movement of money paid for the food by the consumers back to the farmers via the same steps in the reverse direction [28]. Wolfert et al. [28] argued that big data in smart farming is appealing as farmers can either be part of the closed, proprietary systems or of an open, collaborative system. A proprietary system is a highly integrated system of stakeholders bounded by terms and conditions. In contrast, with “open, collaborative systems,” farmers are free to choose any stakeholder as business partners in a food supply chain. In either of the two (closed or open) scenarios, the food supply system enables farmers to exchange information with other actors in a supply chain (two-way traffic), harnessing essential knowledge for production based on consumer needs and other factors in the supply chain.

Smallholder farmers face the challenge of market access for their products [54,55]. Intermediaries force farmers to sell their products at a low price, resulting in unprofitable production. Thanks to ICT, smallholder farmers can access market information and participate in better-paying agricultural production. Market access is a critical component in e-agriculture initiatives in India. Rural farmers are linked to the market and get fair prices, improving income and a sustainable life [42]. ICT-related cases in Africa include “eSoko” in Ghana, “Tru Trade” in Uganda, and “mFarming” in Kenya, Ghana, and Tanzania [81]. These programs address the challenge of access to market information and fair prices for smallholder farmers’ products.

Furthermore, Nigeria’s “E-Wallet Scheme” enables smallholder farmers to access subsidized inputs through mobile phones. Meanwhile, “E-Krishok and Zero Hunger” in Bangladesh and “Farmers’ Advisory Information System” in Tanzania provide extension services to farmers, mainly advising farmers on farm input products [53,54,80,81,87]. These and many other related efforts not included in this paper are promising ICT initiatives for smallholder farmers' access to the market.

5.2.5 e-Government Services in Agriculture

Governments play a crucial role in developing various economic sectors, including agriculture. For a long time, most governments have provided various agricultural services, often through extension agents responsible for connecting with farmers [59]. However, several limitations to using extension agents include the difficulty of reaching the many smallholder farmers scattered throughout rural areas, the inability to deliver multiple agricultural services to farmers, and the high costs involved [88]. Governments play a central role in monitoring, controlling, and bringing together agricultural stakeholders to facilitate service delivery through a single access point, thereby promoting digital technology for sustainable agriculture at the national level. OECD [60] mentioned that ICT promotes government transparency and accountability to the community.

Therefore, e-government provides the government with opportunities to deliver multiple, coordinated, and timely services under one roof through a network of agricultural actors. Ntaliani et al. [61] suggesting that the government should utilize the e-government model to provide services to farmers and rural communities. The Indian government, through the Ministry of Agriculture, supports various ICT programs for smallholder farmers to access essential services, including farm inputs, financial services, subsidies, and markets, thereby increasing production and income [42].

5.2.6 Digital Farmer Profiling Platforms and Services

Apart from precision agriculture and smart farming, many ICT services provide isolated solutions packages to meet farmers' needs. Digital farmer profiling is a business model that has been developed over the past few years to provide essential solutions to the needs of smallholder farmers. The platform service manages farmers' data based on blockchain technology to allow farmers to share their data with other stakeholders (such as credit and insurance companies) [84]. Digital farmers' profiling appears promising for service delivery to smallholder farmers. Studies in Africa, Asia, and Latin America show how digital farmers' profiling enables smallholders to access essential services such as financial services and marketing of their products [82,83,89,90]. Service providers manage the data (for a fee) on behalf of other actors, including the farmers. Despite the long debate over who owns the data (between service providers and farmers), Grameen Foundation, as experienced experts in the farmer profiling platform business model, has stated that the sustainability of the project is a significant challenge once the project fund ends [84]. In addition, Boyera and Grewal [83] concluded that each country and value in the crop or livestock chain would have its own approach to implementing a farmer profiling platform.

5.2.7 Digital Agricultural Technology in Tanzania

The Tanzanian government has consistently supported smallholder farmers and the agriculture sector. Since the 1960s, the government has introduced more than 16 National Agriculture Input Voucher Systems (NAIVS) for farmers to access and use modern farm inputs (seeds and fertilizers) through contracted agro-dealers for improved production and income [91]. The most recent NAIVS is the Inputs Subsidy Programs (ISPs) from 2008 to 2013 and in 2022/2023 [92] However, due to a lack of government control, contracted agro-dealers sell the subsidized inputs at full market prices, leading to a deficient impact of the programs on farmers [65,92]. Indeed, since the adoption of ICTs in national development plans in 2003, numerous ICT-related projects have been undertaken to address various challenges in the agricultural sector. Generally, the target areas are the dissemination of agricultural information by agrarian research institutions (ARIs) and extension services to farmers and farmer organizations (FOs) [59,93].

The increased use of mobile technologies also triggered projects on mobile farm services, such as the Global System for Mobile Association (GSMA) “Mobile for Development” projects and mobile applications to support farmers in different value chains [93]. A mobile application for poultry farmers [94], and mobile decision support systems [95,96]. Furthermore, the design of farmers' digital advisory service called “Ushauri” to provide access to context-specific information from extension agents increases capabilities in decision-making and adaptation to changing environments [97]. These digital services don’t meet the needs of a farmer’s entire ecosystem, nor are they sustainable, as some of the mentioned services don’t exist due to a lack of sustainability plans or because farmers don't utilize the service. Digital technology interventions could help mitigate the challenges and enhance smallholder farmers’ access to services, leading to increased production and income.

In Tanzania, e-Government services in the agriculture sector have witnessed the implementation of M-Kilimo—a web-based and mobile application for farmers to access extension services and market information—a call center for farmers and general agriculture stakeholders, and a fertilizer subsidy distribution platform called the DFSDS, all in favor of smallholder farmers in the country [64]. However, all these digital solutions in developing countries only solve a particular problem, sometimes for specific agricultural value chains, which does little to solve the problems of smallholder farmers as part of a complete farming cycle. John [98], argued that most digital innovations for smallholder farmers utilize complex technology and lack thorough testing, resulting in incompatible systems. Moreover, most digital solutions fail to integrate the components of sustainable agriculture, namely, the sustainability of the ICT infrastructure and the resources that support the digital service, as well as economic sustainability (increased income and productivity) and environmental sustainability.

Despite all efforts, smallholder farmers in Tanzania and other developing countries continue to face numerous challenges in accessing services from various actors within the farmer ecosystem. Challenges include access to credit [99,100], substandard agricultural inputs from uncertified agrodealers [41,102,103], and unfair market prices resulting from the involvement of middlemen and a lack of government oversight [55,56,93,101].

5.3 FDIS Abstract Design

We developed a preliminary design based on challenges identified from the literature (problem-oriented initiation). FDIS is a data management system that brings together key agricultural stakeholders and enables service exchange through data sharing. The initial design of the FDIS platform includes five modules: (1) farmers' data, (2) agro-dealers' data, (3) farm input data, (4) advisory services, and (5) market services, as shown in the conceptual model in Figure 3. Data from farmers and other stakeholders solely drive the platform. Therefore, after establishing the digital infrastructure, the first step is to collect data that different actors can access to provide various services to farmers. We suggest that the FDIS be managed by the government or a public-private partnership, given the crucial role the government can play in networking the agricultural sector by integrating various services under one umbrella. Consequently, a government-led implementation of the system should lead to more sustainable agriculture—covering economic sustainability, environmental sustainability, and the sustainability of ICT infrastructure and resources [6].

5.3.1 Farmers' Data Module

The FDIS data management system for smallholder farmers should comprise comprehensive data for government, donors, investors, and other stakeholders, enabling effective services. Like farmer profiling [83,84], the platform should include personal data that uniquely identifies a farmer, including the national identification number. Personal information should consist of elements essential to the services, such as literacy level, income, language, level of control over the farm, and details of farmer communication to determine their preferred channel of information dissemination, primarily regarding advisory services. Location information of the farmer is also critical for subsidies, tailored insurance, and credit services. Important location details include an administrative address, such as a regional or township, district, ward, division, village, street, and plot number, as well as Global Positioning System (GPS) coordinates. An Application Programming Interface (API) could be used to connect and verify individual farmers' identities in the national schemes of personal identification, such as the National Identification Authority (NIDA) in Tanzania. Blockchain technology is also essential to immutably record uniform and portable personal data [84]. Therefore, farmers could share their data with stakeholders as they wish, such as financial institutions for a service.

Additionally, stakeholders require farm information to identify actual needs and provide targeted support to farmers. Farm details include GPS coordinates, crop type, farm registration information, labor requirements, and equipment used for farming activities. According to Boyera and Grewal [83], sometimes farmers manage several fields in different places, or one piece of land divided into sections for various crops. In this case, land information, such as location, size, ownership, crop type, and soil quality, helps support smallholder farmers. Linked to a field, production information that includes planting details, pests, and diseases, along with their treatments, helps prepare for post-harvest activities.

Most farms in Africa are uninsured; only approximately 650,000 farmers have access to insurance out of more than 40 million smallholder farmers in sub-Saharan Africa alone [47], which is less than 2%. Nonetheless, financial instrument information available to farmers, including credit, subsidies, insurance, mobile money, and bank accounts, is vital for financial services. Credit information enables smallholder farmers to access credit services in line with financial instruments. Credit information includes credit history, farm production plans, and membership in micro-finance institutions. Moreover, insurance information enables other stakeholders to understand the scope of coverage, the level of production risks covered, the type of insurance company, recurring costs, and the amount payable to farmers if the insured risk occurs. The platform offers the opportunity to improve or adopt index-based farm insurance, which scientists and organizations consider particularly effective [47]. These digital artifacts could potentially influence investments in insurance companies that support smallholder farmers in times of crisis.

Agricultural knowledge and farmer training, mainly through farmers' cooperatives, will enable smallholders to participate in modern farming by learning best practices in investment and management of production resources, thereby increasing production and income. Therefore, information on the qualification of the farmers constitutes an essential dataset that has implications for the value of the farm products, which is critical to marketing. Certification and training must be registered at various levels, including farm preparation, planting, pesticide and herbicide use, irrigation, and other farm management activities, such as harvesting. In addition to the marketing segment, business information, namely agribusiness linkages, cooperative membership, market-related to the farmer, quantity harvested and sold (at the farm, cooperatives), and price sold, plays a significant role in connecting farmers to the market [84]. Data about farmers should be as complete as possible to allow quality and tailored services such as subsidy distribution, advisory services, credit, and insurance [102]. Here we present the conceptual solution to the farmers' problems identified in the literature (Table 14).

Table 14. Farmers data and services for sustainable agriculture.

Problem Description	**Data Categories** [103,104]	**Data Type** [103,104]	**Issues to address**
Poor decision, cheating, and fraud in selecting and distributing	Personal information	Full names, identity numbers, gender, family details (marital status, size, family leader gender), land size and	• Transparency in selecting and allocating subsidies

Problem Description	**Data Categories** [103,104]	**Data Type** [103,104]	**Issues to address**
subsidies to smallholder farmers [105].		ownership status, income level, education level, and other sources of income	• Increase trust of other stakeholders, eg, financial institutions
Existing advisory and extension services are often too general for farmers to comprehend and apply effectively.	Communication Information	Language preferences, preferred channel of communication, phone details (number, smart/basic phone, phone literacy), preferred type of information (market, crop)	• Tailored advisory and extension services • The correct information to the right farmers through the proper channel
Distance between farmers and service providers, eg, input traders, is a challenge [106]	Location details	Current and permanent physical addresses: regional/district/ward/division/ plot and GPS coordinates	• Input delivery services and new agro-dealers' investments in demand areas • Useful data from other stakeholders
Inability of service providers to assess farmers' production risks and opportunities.	Farm data	Farm registration, employee/labor, farm tools, crop type(s)/variety	• Tailored advisory services such as inputs, credit, and market services
	Field data	Field location, soil, size, land title, GPS coordinates, and crop history	• Insurance services covering risks linked to the field location and crop type
Poor access to financial (credit and insurance) services [107–109].	Financial instrument	Mobile money and bank accounts; accessed credit, insurance, and subsidies	• Provide payable loans and financial advisory services • Help farmers create good farm business plans
	Credit Information	Credit history, business plan, cooperative societies membership, active credit (loan size and use)	
	Insurance data	Insured field, insurance cost, risks covered, insurance company, amount repaid if the risk(s) occur	• Identify uncovered risks • Useful for credit services (de-risking loans)
The agricultural knowledge of smallholder farmers is unknown; therefore, it is challenging to determine their service packages.	Qualification and certification data	Training and certification dates for different levels and stages of farming, Training/certification institutions Certificates of adherence to farming standards	• Access a unique market, such as organic food products • Advisory service based on the knowledge gap • Identify needs and provide training in anticipation • Increase the quality of products and the environment
Smallholder farmers do not record production information, making it challenging to prepare for post-harvest activities	Production data	Planting data (amount of seeds, date, spacing, tools used, intercropping) Input data (irrigation, herbicides, fertilizer, pesticides) Pest and disease attacks, rainfall, yield, loss, and storage	• Yield prediction and post-harvest activities preparations, eg, storage and market • Real-time advisory and information services to farmers • Early warning services

Problem Description	Data Categories [103,104]	Data Type [103,104]	Issues to address
Poor access to market and middlemen market disruption [110,111]	Business information	Agribusiness linkages, market expectations by the farmer, price, total product sold (at farm, market, corporation), cooperative membership	• Predict different markets that farmers can use • Enable farmers to connect with the market and ensure transparency of transactions

Source: Mushi et al., [66]

5.3.2 Agro-dealers' Data Module

Agro-dealers play a crucial role in distributing farm inputs, enabling smallholder farmers to adopt new agricultural technologies throughout the country; however, a study by Rutsaert et al. [112] on the geographical distribution of agro-dealers in Tanzania shows that most smallholder farmers in rural areas utilize very few modern farm inputs due to the limited availability of agro-dealers' services. The few agro-dealers in remote regions face high demand and less competition, allowing them to charge higher prices to smallholders and have fewer product choices in stock [112]. Furthermore, some agro-dealers and their products are not certified by the authorities, resulting in the distribution of substandard inputs [113], which results in low production, poor quality products, and a negative impact on the environment and consumer health. Most smallholder farmers in Tanzania do not use industrial fertilizers [114] thus, they depend on organic manure and natural land nutrients, decreasing soil fertility and crop production in the short term. As a result, smallholder farmers engage in deforestation to find new arable land, which harms the environment and contributes to global climate change.

The agro-dealers' data module will enable policymakers, government authorities, and investors better to understand the distribution networks of agro-dealers across the country and improve the current situation toward sustainable agriculture among smallholders. By analyzing farmer data and the distribution of agro-dealers, investors can identify opportunities, especially in remote areas, allowing farmers to have a wide choice of stocked farm input products at a fair price. Smallholder farmers will also be able to identify certified agro-dealers and farm inputs to combat substandard inputs from uncertified dealers. Agro-dealers' data should include their business name, administrative address, registration details, location with GPS coordinates, certification, and a list of services, such as delivery and advisory services, offered to farmers.

5.3.3 Farm Inputs Data

Domestically produced or imported agricultural inputs must undergo quality controls and verification before being distributed. Like many African countries after independence, the importation and distribution of farm inputs in Tanzania were centrally controlled by state organizations. Until the 1970s, the government had the Tanzania Seed Company for seeds and a state monopoly on fertilizer distribution at subsidized prices, as outlined in the 1967 Arusha Declaration. However, the state then faced a debt crisis, delays, and shortages in input distribution, and allowed the private sector to enter the market[114]. Many private sectors are involved in importing and distributing farm inputs registered and certified by government authorities. Despite the involvement of the private sector, only about 15% of the seeds planted are registered and approved by the responsible authorities, and about 2,500 tons of agrochemicals were registered in Tanzania in the mid-2000s [114]. Studies suggest that informal farm inputs smuggled across neighbouring countries dominate the market.

Moreover, most of the pesticides and seeds in Tanzania are counterfeit in various ways, including reprinting product labels, diluting chemicals, and copying package shapes. For these reasons, Tanzania has had a low yield per hectare compared to other developing countries. For example, the average yield of maize is 1.5 tons per hectare, while the World Bank estimates 6–7 tons when farmers use adequate and quality inputs [115].

Publishing and sharing data of the registered and certified farm inputs would solve the problem of substandard farm input distribution. Essential data about farm inputs includes the manufacturer's details, international registration details, information about the importing or supplying agent, registration and certification data provided by Tanzanian authorities, usage data, and a unique verification code. Therefore, farmers will be able to identify registered agents or suppliers and verify the originality of farm inputs, such as seeds, fertilizers, and agrochemicals. The effort also requires a campaign to sensitize farmers to use quality farm inputs and their benefits.

5.3.4 Advisory Services Module

The lack of comprehensive advisory services is a significant factor contributing to the low adoption of modern farming techniques among most smallholder farmers[116]. The Tanzanian government employs outreach officers to disseminate information and advise farmers on modern farming practices, including the use of farm inputs, to address the problem. The Tanzania Agriculture and Livestock policy, revised in 2000, defines outreach services as the transfer of agricultural technology from experts to farmers, livestock keepers, and other stakeholders [117]. However, outreach officers are limited by the number of farmers they can visit; thus, most smallholder farmers rely on traditional farming knowledge from other farmers and family members. In addition to the farmers' advisory information system developed and implemented by Sanga et al. [87], the FDIS can provide more tailored advice from experts based on farmers' data, such as location, type of soil, crop, and farm equipment. Agricultural Research

Institutions (ARIs), through information and outreach services sections such as the Sokoine National Agricultural Library (SNAL), provide outreach information services to farmers across the country [118]. Therefore, ARIs could utilize farmers' digital information systems to repurpose information based on the needs, literacy level, crop or livestock type, and other attributes of smallholder farmers for effective advisory and outreach services.

5.3.5 Market Services Module

The farm product market is the core of agribusiness success and economic sustainability. The FDIS for farmers will provide market data, including information on various markets and product prices. This information is crucial for smallholder farmers to identify the right market for their products and thus earn a fair income. Furthermore, the platform will enable farmers to publish their yield information and meet directly with potential buyers, eliminating the need for intermediaries in the value chain. Thus, farmers will have numerous market options through cooperatives, trade channels, and on-farm sales, which are informed by market price information.

5.4 A Refined FDIS Design

5.4.1 Stakeholders Opinions

We introduced the preliminary design to key agricultural stakeholders in Tanzania through a survey, which identified additional needs and refined the artifact design (see Chapter 4). The agricultural stakeholders surveyed include the Ministry of Agriculture (MoA), crop farmers, livestock keepers, agrarian insurance companies, financial institutions, extension workers, agro-dealers, and customers of agricultural products. The survey allowed us to assess the validity of our model's hypotheses, which are based on case studies (presented in the next Chapter). Moreover, it presented stakeholders' opinions on the challenges they face and their recommendations for refining the FDIS to meet the needs of agricultural stakeholders in Tanzania.

Indeed, the findings reveal that the stakeholders were ready to accept the FDIS design given the envisaged platform has the potential to solve many of their current challenges present in the complete farming cycle and could further motivate farmers and other stakeholders to target a more sustainable agriculture, to increase production and income, and be more respectful to the environment. Opinions from key stakeholders in the agricultural sector suggested modifications to the FDIS functionality, necessitating the development of a more refined artifact. Indeed, the stakeholders had a positive impression of the preliminary design and recognized its potential implications for sustainable agriculture. The additional services proposed for the FDIS design include transport and logistics, permit services from the authorities, and information on warehouse services.

5.4.2 FDIS Additional Modules

Logistics services have emerged as an essential feature in the FDIS design, as proposed by agro-dealers, MoA, farmers, and customers. Agro-dealers are facing the challenge of transporting inputs from manufacturers and importers to different regions in the country. Moreover, logistics services are key in the envisaged platform as farmers can order inputs for delivery. Agricultural produce from the farm to warehouses, then to the market, and from processing industries to consumers requires logistics services in place. Therefore, stakeholders should be able to request services from logistics companies through the FDIS. The MoA suggested that different permits from the authorities, such as permits for harvesting, transporting, importing, and exporting agricultural products, be included in the FDIS design to improve efficiency and offer timely services to stakeholders. Farmers proposed warehouse services on the envisaged FDIS platform to identify the availability of warehouse space and request it using their handheld digital devices or computers. Figure 6 presents both the preliminary and refined design, with the highlighted parts of the FDIS design showing the additional functionalities as suggested by the stakeholders.

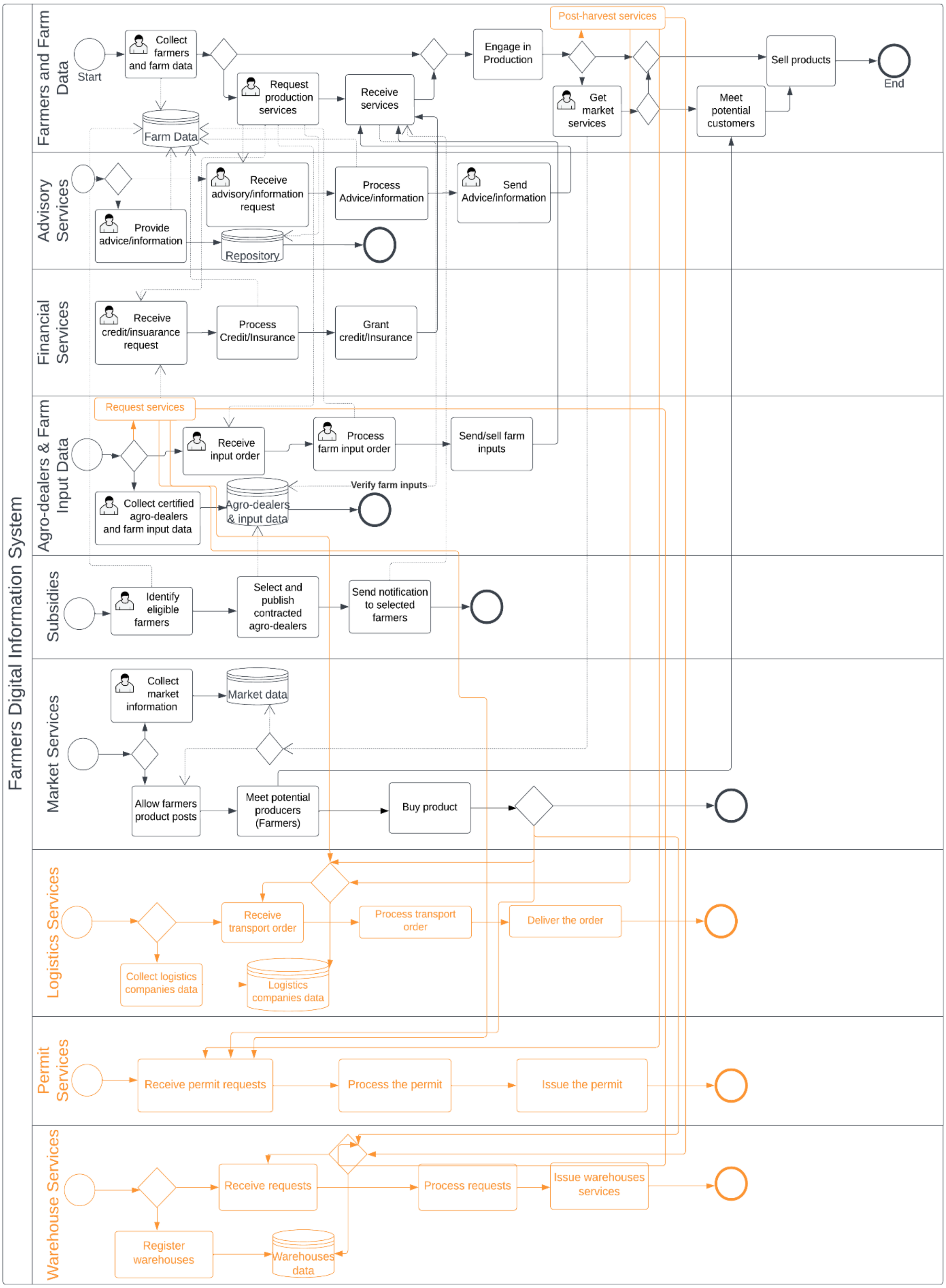

Figure 6. A refined FDIS Business Process Modelling and Notation (BPMN) diagram (changes shown in orange) [119]

Chapter 6

Architecture, Proof of Concept of FDIS and Impact on Tanzanian Agriculture

6.1 Introduction

The validation of the innovative digital artifacts followed a successful FDIS design. We described the applicability of FDIS in solving challenges and providing services to the smallholder farmers through the illustration of four cases in Tanzania. The illustration explains how FDIS would address the issues related to subsidies, farm inputs, financial services, and market access. Moreover, we provided a proof of concept of the FDIS to demonstrate various functionalities and services to smallholder farmers and other stakeholders.

6.2 Illustration of Four FDIS Cases

6.2.1 Subsidies

The Tanzanian government has supported smallholder farmers through subsidies since independence. From the 1960s to the early 1970s, the government monopolized the agro-inputs market and controlled importation and distribution at subsidized costs, enabling smallholder farmers to increase production and income. Later, in the mid-1970s, the government faced a colossal debt crisis, delays in input delivery, and a shortage of these products, which allowed the private sector to enter the market [114]. Nevertheless, the government maintained the subsidy programs for smallholder farmers through contracts with private suppliers. Since its independence, Tanzania has had 16 NAIVS contracts between the government and input suppliers [91]. The agreements require suppliers to sell inputs such as seeds, fertilizers, and agrochemicals at half-market price to selected smallholder farmers. The study on the effectiveness of the NAIVS suggests that the programs had a low impact on smallholder farmers due to cheating and fraud [91]. The subsidies did not reach the targeted farmers due to biases in the selection process, as contracted agro-dealers refused to participate in the program and therefore sold inputs at full market prices to subsidized farmers. For this reason, the majority of smallholder farmers do not use quality farm inputs, resulting in low production and income.

The FDIS data management system for smallholder farmers has the potential to solve the fraud and cheating in the distribution of subsidies. Data about farmers and agro-dealers is essential for transparency in selecting smallholder farmers and accessing farm inputs from contracted suppliers at a half market price or under any other agreed-upon conditions. Suppose the subsidy coordination office uses the FDIS to select smallholder farmers. Then it will be possible to allocate subsidies to them based on specific criteria and send them notifications with a list of contracted agro-dealers from whom they can purchase subsidized farm inputs. The FDIS could provide data on selection criteria such as women-headed families, low-income families, farm size, and land ownership to facilitate the selection of appropriate smallholders. At the same time, farmers will be able to identify contracted suppliers directly. As a result, the targeted smallholders will be more likely to adopt the new technologies, thereby increasing their productivity and income. The system could ultimately improve the impact of NAIVS programs in Tanzania and reduce extreme poverty and food insecurity among a growing population.

6.2.2 Farm Inputs Supply

After the liberalization of the input market, the government formed agencies for different input quality verification and registration for local and imported farm inputs, such as, the TFRA for fertilizers, the Ministry of Agriculture, Food Security and Cooperatives – seed unit (MAFSC-Seed Unit), the Tanzania Official Seed Certification Institute (TOSCI) for seeds, the Tropical Pesticides Research Institute (TPRI), and the Tanzania Atomic Energy Commission (TAEC) for agrochemicals verification and registration [114]. These agencies aim to ensure the quality of inputs for increased production and environmental preservation. The quality of farm inputs is among the factors contributing to increased production and income so that farmers can get a return on their investment. However, studies show that 85% of seeds planted in Tanzania are not registered, and the input market, mainly agrochemicals, is dominated by products smuggled from neighboring countries [114]. Regular operations by government authorities in agro-dealers' stores uncover substandard inputs that contribute to low production and high risks to human health and the environment. For instance, 'less than a quarter of agro-dealers are checked each year, and the amount of counterfeit seed circulating in the market is estimated to account for at least 25–35% of all commercial seed' [114].

On the FDIS platforms, data on inputs registered and verified by regulatory authorities will be published, allowing farmers to access inputs from registered agro-dealers. Imagine a farmer using the FDIS on a smartphone, tablet, or computer to search for verified quality of farm inputs: they will be able to find the nearby registered agro-dealers and verify the inputs through a FDIS platform, as shown in Figure 7. The platform could include a digital verification for incoming products, such as a barcode or quick response code for easy verification. Such a practice will also enable the automatic removal of unregistered products and agro-dealers from the market.

6.2.3 Financial Services

Smallholder farmers have limited access to credit and insurance services [99], which hinders their uptake of quality farm inputs and modern farm equipment, thereby limiting production increases. However, agricultural financing has a potential role in sustainable agriculture among smallholder farmers globally. Tanzania has experienced low agricultural production in the long term despite its abundant arable land and favorable climatic conditions. Many studies link low output to a lack of access to credit services; most poor farmers are unable to adopt new technologies and farm inputs to increase production [114]. The majority of smallholder farmers, particularly in rural areas, rely on cooperative institutions as a primary source of credit. Cooperative institutions are formed locally, and loans are only granted to known members of the association who provide micro-savings as collateral for the loan [99]. However, loans from cooperative institutions are limited by members' micro-savings, which restricts the farmers' ability to invest in agriculture. A study on access to credit in Tanzania reveals that only 1% of total bank lending is allocated to the agricultural sector. The banking industry in Tanzania anticipates high risks of lending to smallholder farmers [45]. Most farms are uninsured due to farmers' financial illiteracy, low willingness to pay, and lack of trust in insurance providers [40].

FDIS - a data management system for smallholder farmers is essential for access to financial services in Tanzania. Credit services could enable farmers to adopt modern farm equipment and high-quality inputs, leading to increased production and income. Farmers' data can be shared with financial institutions through APIs. For instance, a farmer using the FDIS platform could apply for a financial service, and the financial institution could request that the farmer share their information for evaluation purposes. Comprehensive data on farmers, farms, production, insurance, credit history, and business information can help reduce the banking industry's lending risks to farmers. The information would enable financial institutions to analyze the highest loan amount a farmer can afford, their ability to pay, and recovery measures if they fail to repay the loan. Likewise, insurance companies can employ a similar approach to provide insurance services to smallholder farmers. Index-based agriculture insurance, which seems promising for smallholder farmers [47] requires farmers and field data to analyze the potential risks of farmers who need to be insured. Access to credit and insurance will increase smallholder farmers' confidence and investment in agriculture, thereby fostering economic development, increased production, and employment opportunities, especially for the most unemployed youth in urban areas, ultimately reducing poverty and food insecurity.

6.2.4 Market Services

Market access has been a critical challenge to most smallholder farmers in developing countries, including Tanzania. A lack of market information is a significant bottleneck for smallholder farmers to participate in the agribusiness sector. Middlemen take advantage of farmers' lack of market information by buying at a low price, usually on the farm, and selling the product at a high cost to the consumers [55]. It is heartbreaking: a report from Tanzania mentions that many farmers aim to produce mainly for (low) consumption because of regular losses in the market when they want high production for their business [56]. Most smallholder farmers practice subsistence agriculture, avoiding risks that could lead to higher production and increased income, which could help address the country's malnutrition problems and make the agricultural sector more dynamic.

The use of the Internet and Information Technology (IT) has a significant impact on selecting productive sales and marketing channels, increasing farmers' income [120]. The market module of the FDIS framework will provide updated information on different markets and product prices. This information is crucial for farmers when negotiating the sale of their products to aggregators, consumers, agro-food processors, and other market stakeholders. A farmer with an FDIS platform on his/her smartphone, computer, tablet, or other device could access the market price of all products (the farmer can use information to decide on future crops to plant, livestock, or post-harvest planning), use the virtual market for farm products by directly meeting potential buyers at a reasonable price (thus eliminating intermediaries in the market value chain), resulting in an incentive for increased production and income for smallholder farmers.

6.3 FDIS Architecture and Proof of Concept

The proof of concept of the three functions demonstrated FDIS capabilities in providing financial services, expert advice, and market services. Indeed, these three services provide farmers with access to economic, advisory, and market services via digital devices, including smartphones, tablets, and computers. Figure 8 below shows a Unified Modeling Language (UML) component diagram that corresponds to the architecture of a complete FDIS-designed service, as shown in the BPMN in Figure 7.

On the left of Figure 8, the farmers' services component can be seen, which is itself composed of several sub-components (farmer database, get advisory service, get financial service, get agro-dealers services, get subsidies service, manage harvest, and manage market). These components communicate with the components (shown in the middle of the figure), providing those services to the farmers (advisory, financial, agro-dealers, subsidies, logistics, and market services). Those services, in turn, require access to additional services, as indicated by the components on the right side of the figure, such as permit or warehouse services. The four service modules highlighted in color in Figure 7 below correspond to the components provided as a proof of concept for the demonstration. The UML component diagram illustrates the deployment of the FDIS platform and service interactions, addressing critical challenges faced by farmers and other stakeholders in achieving sustainable agriculture.

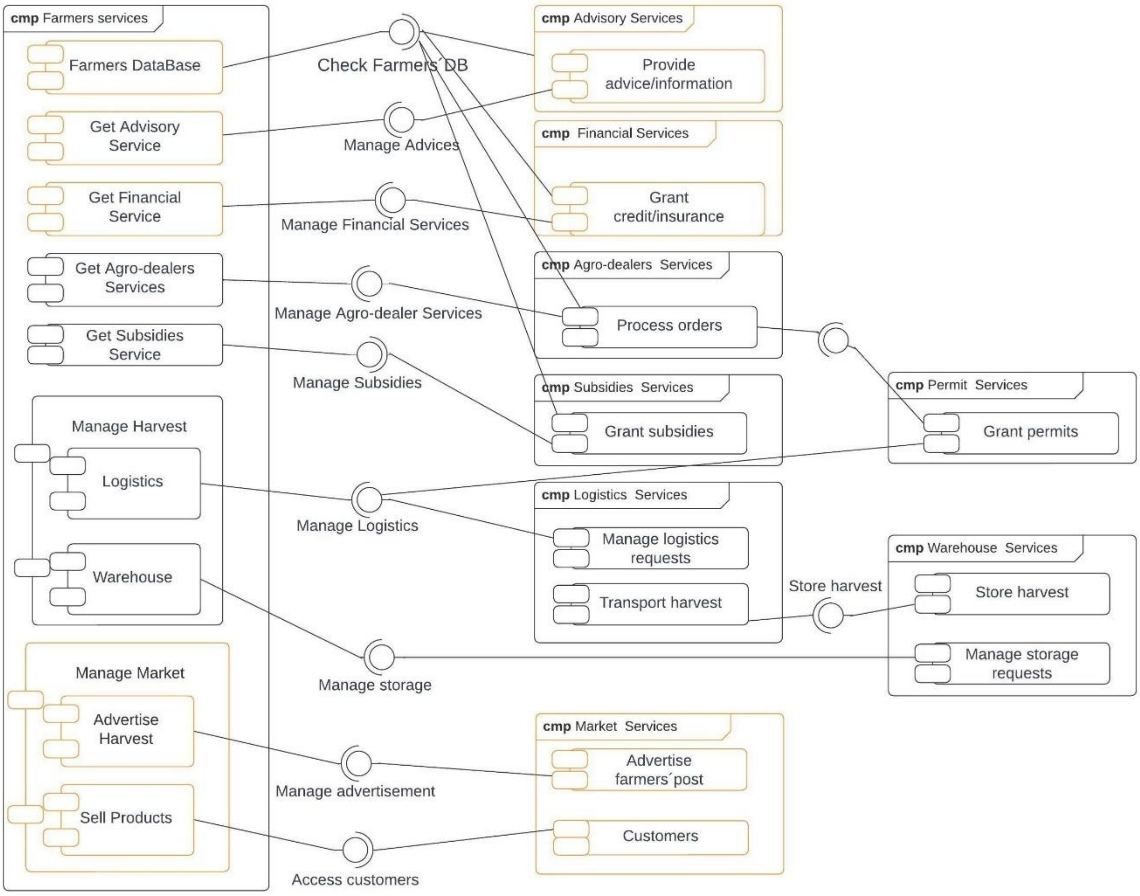

Figure 7. FDIS UML component diagram (proof of concept part shown in orange) [121]

More precisely, FDIS comprises several essential services that bring together all key stakeholders in the agriculture sector, including the government. The fundamental component of FDIS is the “farmers' services” component (left side of Figure 8). This component hosts several sub-components, including the farmers' database, from which other stakeholders can request data during the delivery service. The farmers' database provides comprehensive information about farms and their owners. Other sub-components of the farmer services include access to advisory, financial, and agro-dealer services, as well as subsidy services, along with two components for managing the harvest and market (advertising and selling products). FDIS also comprises components for service providers (in the middle of Figure 8), such as financial services (including credit and insurance), advisory services, agro-dealers, and subsidies. The agro-dealer service is further linked with the permit service. These services require data from farmers to ensure quality and timely service delivery; additional components concern services related to logistics and the market. The harvest and logistics services are further linked with the warehouse services for storing the harvest. Therefore, farmers can request and receive services from all the stakeholders through the system that can be accessed by all mobile devices (Android and iOS) and also from the website. Subsidies in Tanzania are government-initiated services; thus, the responsible department uses farmer data (collected after registration) to deliver the service (see Figure 8). For the market service, farmers are expected to post their farm products so that interested customers can contact the farmer for business.

6.3.1 Financial Services

According to Kirui et al., [46], Simbakalia [45], and Kimaro [100] farmers lack investment capital because they rely on their assets to invest in production. A survey conducted under this project revealed that only a small number of farmers approach financial institutions for services in Tanzania. Meanwhile, farmers experience lengthy application procedures and denial or have insufficient credit needed for production. On the other hand, the financial institutions consider farmers as high-risk customers and impose strict conditions for access to credit services [122]. Therefore, the majority of smallholder farmers are unable to invest in modern farming and animal-keeping, resulting in poor production, low income, and environmentally unfriendly agricultural practices. The poor relationship between smallholder farmers and financial institutions is due to a lack of data. There are no reliable data that introduce farmers to other stakeholders for a service. For example, for a bank to verify the information provided by farmers when applying for a loan, it must call on its agent to physically visit the farm, interview neighbours and local authorities, etc. Farmers have complained about the time it takes to obtain a loan, and most of them receive the loan when the time needed for farming has elapsed. As a result, they use the loan for other unplanned purposes, which prevents them from repaying the loan [122]. This vicious cycle of mistrust and lack of cooperation is hampering the growth of the agricultural sector and efforts to eradicate extreme poverty and hunger in the global community.

The digitization of the financial service within the FDIS platform was designed to solve the problem of data management for smallholder farmers. The platform accurately collects farm and farmer data to share with other stakeholders as a service. FDIS was designed to collect all essential data needed by different stakeholders, including financial institutions. These dataset categories include personal information, communication information, location details, farm and field data, financial instruments and credit information, insurance, production data, and business information [66]. Data collection on the platform involves various actors and multiple levels of verification for quality assurance. FDIS applies data shielding during data sharing for services to adhere to the privacy and security of data. Therefore, not all farmer data will be openly available when exchanging services with stakeholders. Pre-defined conditions for data access by each stakeholder must be defined to ensure that each stakeholder has access to sufficient data to enable the provision of services to farmers. For instance, financial institutions could utilize FDIS to request and access farmer data, such as the manual forms used to collect data from farmers when applying for services.

FDIS could increase efficiency and collaboration between smallholder farmers and financial institutions. Smallholder farmers can apply for credit services by simply sharing the necessary information with financial institutions. Simplified verification of farmer information by financial institutions could lead to timely credit services, grant sufficient loans required for production, and improve access to financial services for smallholder farmers. The survey carried out as part of this project revealed that one of the reasons for the poor relations between smallholder farmers and financial institutions is the lack of data on farms and farmers. FDIS can promptly provide financial institutions with comprehensive information on farms and farmers. Information such as the business plan, production history, and farm financial statements is crucial for evaluating the farm's financial stability and for effective risk management. This information is vital for reducing the risks associated with loans granted by financial institutions, as well as for providing other credit services effectively. Moreover, integrating AI in FDIS could facilitate crop yield prediction based on the farm data, such as farm size and type of crop.

6.3.2 Advisory Services

The digitization of information and advisory services to smallholder farmers could address numerous economic and environmental challenges in developing countries, including Tanzania. It should be noted that most smallholder farmers do not have access to modern agricultural farming knowledge or expert advisory services, so they rely on their expertise and that inherited from the farming community [64]. A recent study on the extended knowledge system in Tanzania revealed a disconnect at multiple levels, thereby hindering the adoption of sustainable agriculture among smallholder farmers [123]. This leads to poor farming practices, such as poor selection of breeds and the use of sub-standard farm inputs, posing a serious threat to the quality and quantity of production, the health of farmers and consumers, and the environment [113,116,124]. A survey conducted as part of this project revealed that most farmers lack training in adopting basic farming and animal-keeping practices and technologies. For these reasons, the Tanzanian government employs extension workers—agricultural experts who transfer knowledge and technology from various sources to farmers. These extension workers work closely with farmers at the ward level. However, this method of transferring knowledge is ineffective because of staff shortages and the difficulty of reaching large numbers of farmers in remote areas [122]. However, some other parts of the country are using radio and short message service (SMS) to disseminate and access extension information, with radio being the preferred channel for sharing information with smallholder farmers [125]. Figure 9 presents the front-end (or interface) of advisory services, enabling farmers to access and request information on various farming activities, such as seeds, farm machinery, crops, crop diseases, labor sources, pests and diseases, and farm inputs. It is the interface that is presented to the farmers to obtain access to the services. It corresponds to the FDIS, get advisory service components highlighted in color on the left side of Figure 7.

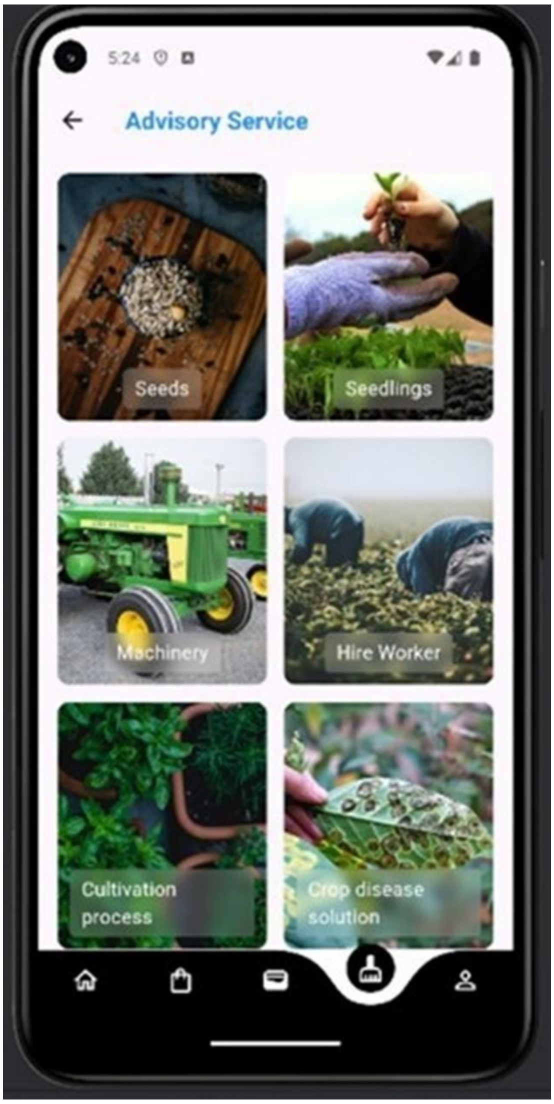

Figure 8. Advisory services—a part of the FDIS proof of concept (farmers' access)[121]

Figure 9 shows six advisory services available for the user. The user can select a service category for more specific needs, such as a particular type of crop disease under the "crop disease solution" or a specific crop cultivation process under the "crop cultivation" category. We provide these few advice categories for demonstration purposes, but other advice categories may be introduced as part of the actual implementation of the FDIS platform.

The FDIS platform's advisory services are designed to address the challenges identified in sustainable agriculture. It involves the registration of agricultural experts and [66]. The experts will be registered in the system and will be able to respond to the various information or advice needs of farmers. This addresses the issue of farmers' reliance on their knowledge in all farming activities, including the application of farm inputs. The ability of farmers to request and receive information and advisory services on various farming activities is crucial for increasing productivity and income, as well as avoiding inferior inputs that could harm the health of farmers, consumers, and the environment. The systematic adoption of these practices and other FDIS services would ensure that smallholder farmers are committed to sustainable agriculture.

6.3.3 Market Services

Smallholder farmers could increase their income and profitability if they found a reliable market for their products without intermediaries in the supply chain [66]. Intermediaries (middlemen) play the role of information brokers. They identify areas where farmers are selling their products at low prices because they lack market information, usually before or shortly after harvest. Intermediaries set the cost for farmers and buy without government control, selling at higher prices to processors and consumers [55]. This practice demotivates farmers and diminishes their ability to increase their investment in agricultural production [126]. We conducted a survey of farmers, processors, and consumers, among other stakeholders. The results revealed that farmers mainly sell to intermediaries at very low prices, while processors and consumers buy from intermediaries at higher prices [122]. Processors and consumers believed that buying directly from farmers could not only increase their profitability but also enable them to purchase agricultural products at a fair price, unlike through intermediaries. However, the lack of information and communication between the farming processing industries, consumers, and farmers is a challenge that intermediaries exploit. To avoid the frustrations of the market and the inability to grow, farmers cut back on production, as they primarily aim for subsistence rather than agribusiness, leading to a shortage of food and raw materials produced by agriculture.

Figure 10 below illustrates the interface of market services that enable farmers to showcase their products and connect with potential customers. It is the interface presented to farmers that allows them to access market services. It corresponds to the FDIS manage market component highlighted in color on the left side of Figure 7. This interface shows three cereal crops as examples of the FDIS platform: rice (also known as paddy), wheat, and maize.

Figure 9. Market service—another part of the FDIS proof of concept (farmers' access)[121]

Customers can navigate to any of the cereal crops they wish to buy directly from farmers. After selecting the crop, customers can browse a list of products posted by farmers, which includes price tags, location, farmer contact details, and information on the quality and quantity of produce. This information is crucial in enabling customers to decide whether to purchase the products. We provided the three crops solely for demonstration purposes, but other crops may become accessible when the platform is fully implemented.

FDIS is designed to link all the key stakeholders in agriculture, including farmers, processing industries, and consumers. This link could radically change the supply chain for agricultural products by eliminating intermediaries. In addition to access to market information, farmers would be able to market their products directly to potential customers, including those from the processing industries and consumers. The survey revealed that on the one hand, farmers would be able to sell their products at a fair price and earn a deserved income if the platform enabled them to access market information and reach a broader market; on the other hand, the processing industries believe that buying raw materials directly from farmers reduces production costs and the cost of processed food for end consumers [122]. As a result, farmers can increase their investment in agriculture and productivity, which promotes sustainable agriculture and the development of the majority of people employed in the sector.

Indeed, Chapter Six explains the applicability of the FDIS platform with different cases in Tanzania. The proof of concept demonstrated smallholder farmers' access to other services, leading to the adoption of sustainable agricultural practices. Chapter Six discusses the necessary environment required for the successful implementation of the envisaged platform.

Chapter 7

Towards the FDIS Implementation in Tanzania

7.1 Introduction

The implementation of the information system requires careful planning and consideration of various contextual environmental issues. These include the willingness and capabilities of the potential beneficiaries, as well as the infrastructure, financial, and human resources necessary to sustain the implemented digital platform. This chapter discusses the infrastructure and other investments for FDIS sustainability, issues related to data, and the way forward to the effective implementation of FDIS in Tanzania.

7.2 Infrastructure and Other Investments for FDIS Sustainability

Several factors surround ICT projects to ensure their successful implementation and sustainable operation. While a critical enabler, investment in ICT infrastructure alone cannot produce the desired socio-economic impact [127]. Therefore, complementary investments such as good policy, an education system, stable electricity service, a skilled workforce, and other resources are essential for the sustainability and maximum impact of ICT projects [128].

The proposed FDIS is an ICT project that aims to have a socio-economic impact at the national level by enabling smallholder farmers to access essential services that maximize their production and income. The envisaged system requires investment in ICT infrastructures such as communication networks, data centers, Internet services, ICT devices, and other related tools, which drive the impact [129]. Samoilenko and Osei-Bryson [129], added that these drivers attract activities, investments, and resources such as a skilled workforce, electric service, and sound policy for successful and sustainable operations for the desired socio-economic implications. Current investment in ICT infrastructure, particularly wireless communication [130], rural electrification [131]; rural farmers are increasing mobile usage and Internet access [132] In Tanzania, there are promising drivers for the implementation and sustainable operation of the FDIS framework. In addition, the national education system fosters the availability of a skilled workforce, including ICT specialists, data management experts, logistics personnel, and other essential human resources needed to achieve the country's maximum socio-economic impact. ICT in support of the country’s agriculture development policy is also critical to the planned implementation of the FDIS, stakeholder adoption, and sustainability of the platform. For instance, an ICT policy to digitize the national agricultural system could rally all stakeholders, identify new areas of skill development, logistics, and food supply chain development, as well as other necessary events to achieve the desired economic outcome.

7.3 Data Management Related Issues

FDIS is a data-driven artifact solution for smallholder farmers. Therefore, implementing the solution requires prior consideration of various data-related issues. These issues include data protection, data quality, data ownership, and sovereignty.

7.3.1 Legal Issues on Data Protection

FDIS collects, stores, and shares personal data with third parties for services to smallholder farmers. In 2023, Tanzania launched personal data protection legislation (The Personal Data Protection Act) to control the collection, storage, and sharing of personal data [133]. However, for countries that are yet to have a legal framework, FDIS will require implementing a specific process aligned with the legislation. The common principle of 'purpose limitation' can be applied to protect both personal and non-personal data, so that the data should not be used for any purpose other than those consented to by the farmers and other stakeholders [82]. Although requirements among countries vary, the common legislation for collecting, storing, and sharing personal information requires the farmers' consent. It lets them know the purpose and the list of organizations with which the information will be shared [83]. Therefore, the implementation of an FDIS will require a training and awareness campaign for smallholder farmers on the purpose and benefits of collecting, storing, and sharing their data with other stakeholders. Farmers will also need to sign consent forms to allow the sharing of information with stakeholders who provide the necessary services throughout the complete farming cycle.

7.3.2 Data Ownership and Sovereignty

Data sovereignty is a rich and multidimensional concept, but it is usually tied in some way to control of the data life cycle, i.e., collection, storage, access, use, reuse, and deletion [134]. Data sovereignty also raises concerns about government authority over data hosted in foreign clouds, as it depends on the laws of the country in which the data is located [135]. Moreover, the introduction of data management model solutions in agriculture poses new challenges to data sovereignty, as agricultural technology providers can take control of the data collected [102]. Consequently, the question arises who owns the data between the farmers, the companies, or the organizations that manage the digital platform? The simple answer is that farmers own the data, sometimes mentioned in the contracts; however, this may not be addressed in them [82]. The complexity of data ownership and legislation stems from its intangible nature compared to other objects. FAO [82], mentions that legally, data is not exhaustible: it can be copied, transferred, and migrated, and the same data can be in different locations and owned by different people. As an ad hoc solution, the FDIS platform could adopt existing legal and regulatory frameworks addressing data ownership [136], as future legislation may resolve some issues related to data ownership.

Similar to a digital farmer profiling platform [84,136], an FDIS collects data that can be 'captured' – leveraging the data collected from the users of the platform for commercial purposes, potentially selling the data to investors, advertisers, product or service innovators [137]. Schrijver [138] mentioned that giving farmers control over their data flow to other stakeholders builds trust with farmers for data exchange and benefits services for sustainable agriculture. Therefore, farmers and stakeholders should have ownership and control rights, including the ability to decide on data sharing for other purposes and its reuse, thereby preventing agricultural technology providers from taking it. Indeed, farmers should control and decide on the data generated by their actions to benefit all partners involved and not fall victim to a 'data grab' that only benefits agricultural technology providers [102,137]. For instance, through an open data charter that enables the design of open repositories for farm data, farmers could share some or all of their data, such as data from a particular farm or crop, with a partner to facilitate planting, chemical or fertilizer application, and post-harvest services, among others. [102,137,139]. In addition, an FDIS requires a legal and regulatory framework that grants 'data owners' the right to delete their data and opt out of the platform entirely, thereby ensuring ownership and protection of farmers' data, which, without stricter rules, is currently being allowed to be taken over by agricultural technology providers [102]. Increased public and private sector investment in ICT infrastructure in Tanzania [130] could attract domestic hosting of the FDIS framework to achieve data sovereignty. However, foreign clouds could also be helpful with a high encryption mechanism to protect data from unauthorized access and use [140].

7.3.3 Data Quality

Data quality is essential for the FDIS to effectively and efficiently provide services to the farmers and stakeholders involved in a complete farming cycle. In this regard, data quality refers to the completeness, timeliness, accuracy, consistency, and precision of the data. The FDIS will collect and capture static (i.e., personal information) and dynamic data that require regular updates, such as crop status and production information. FDIS could utilize APIs to connect and verify farmer identities in national personal identification systems, ensuring consistency in individual farmer data. As an incentive, it is essential to train farmers and other stakeholders on the importance of updating their data and addressing quality issues, not just those related to provider services. Autonomous data collection, such as sensors and unmanned ground and aerial vehicles (UGV and UAV), can ensure data quality; however, these tools require a substantial upfront investment [141]. In general, the manual tasks of data collection and update could involve well-trained staff, including extension agents, in collaboration with farmers and other stakeholders. Indeed, as part of the data quality control process, FDIS will apply verification and validation procedures to ensure the validity and reliability of the data.

7.4 Effective Implementation of FDIS

Although FDIS has the potential to make the agricultural sector more dynamic and sustainable, several issues need to be considered for its effective implementation. FDIS is a comprehensive digital platform that requires the efforts of various key agricultural stakeholders, including experts from different disciplines, as well as governmental and non-governmental organizations. Smidt and Jokonya [142] ascertained that government and institutional support are critical to bringing together agricultural stakeholders and to developing a localized developmental implementation framework for supporting the adoption of digital solutions to support smallholder farmers. The FDIS platform is a data-driven digital solution to the challenges faced by smallholder farmers in developing countries. Farmer and farm data are the key components of the FDIS platform, and farmers, service providers, and other stakeholders can share these data when requesting and providing services. This raises issues of data quality (completeness, accuracy, timeliness, and precision of data), data ownership and sovereignty, as well as legal matters related to data protection. Implementing the FDIS platform will require training stakeholders on the importance of data quality and training staff responsible for collecting and regularly updating the data. Moreover, FDIS could use the Application Programming Interface (API) to verify stakeholder data from existing systems such as the National Personal Identification System. More advanced technology, such as sensors, unmanned ground vehicles, and unmanned aerial vehicles, could be used to collect quality data; however, such technology requires a considerable initial cost [141].

Data ownership and sovereignty have become a critical topic of discussion when implementing data management systems. The debate over data ownership between farmers, companies, and the organizations that manage digital platform infrastructure continues to be ongoing. Many existing data ownership models indicate that agricultural technology providers are increasingly taking control of data and reusing it for their benefit [102]. Although new policies transfer ownership of data to farmers, the problem of data dispersal persists; data can be copied, transferred, and migrated, and may exist in different locations and under varying ownership [82]. Nonetheless, good practice of data ownership can be adopted when developing policies governing the implementation of data-driven systems. For example, an open data charter would allow farmers to share all or part of their farm data with service providers, such as fertilizer companies, while giving data owners (farmers) the right to delete their data and opt out of the platform, thereby exercising data ownership and protection [102,137]. Many governments of developing countries are developing policies and legislation on data protection and data sovereignty. For instance, in 2023, Tanzania launched personal data protection legislation (The Personal Data Protection Act) to control the collection, storage, and sharing of personal data [133]. However, for countries that are yet to establish such as legal framework, common legislation can be used to implement the FDIS platform, according to which the collection, storage, and sharing of personal data require the consent of farmers, who must be aware of the purpose for the data collection and the list of companies or organizations with which the data will be shared [83].

FDIS is a complete digital artefact designed to digitize the national agricultural system. Therefore, the effective implementation of FDIS requires enormous resources, namely, infrastructure, trained staff, and financial resources. The partnership between the government and the private sector could benefit from utilizing existing infrastructure and resources to adopt the FDIS platform. For example, the Tanzania Ministry of Agriculture (MoA) has invested in digital technology to serve farmers and other players in the country's agricultural sector. ICT-based services implemented by the MoA include M-Kilimo, which is a web and mobile application for farmers to access extension services and market information, a call center for farmers and agricultural stakeholders in general, and a fertilizer subsidy distribution platform called the DFSDS, all for the benefit of smallholder farmers in the country [64]. FDIS can inherit existing infrastructure, human resources, and data from farmers and other stakeholders, eliminating the need to start from scratch. Moreover, other government employees, particularly agricultural extension officers (employed throughout the country), could play a key role in the collection and regular updating of farmer data on the platform. All of these elements could significantly reduce the cost of implementing FDIS while also ensuring the quality of the data and services, and guaranteeing the sustainability of the infrastructure and resources that support the platform.

Chapter 8

Conclusion

Digital technologies have the potential to alleviate extreme poverty, ensure food security, and conserve the environment by making the agriculture sector more dynamic and sustainable. This thesis focuses on digital solutions to enhance the participation of smallholder farmers in sustainable agriculture, with a case study in Tanzania. It presents and demonstrates the development of the FDIS platform solution to address the common challenges faced by smallholder farmers in low- and middle-income countries. Although FDIS is promising for smallholder farmers participating in sustainable agriculture, effective implementation could face various challenges. However, the collaboration of key stakeholders, particularly the government and the private sector, is crucial to the successful and sustainable implementation of the FDIS platform.

Chapter Eight provides a comprehensive summary of the study's scientific contributions, reviews the research questions, and discusses the study's limitations. Moreover, it highlights potential areas for future research whereby digital technologies could enhance productivity and income for most smallholder farmers residing in rural and semi-urban areas of developing countries.

8.1 Summary of Scientific Contribution

This section presents the main scientific contribution of the research. It is a summary of five peer-reviewed scientific articles that align with the research objectives. More details about the articles are presented in Table 5 below.

The research primarily focuses on designing and implementing a digital platform that enables smallholder farmers in Tanzania to access all essential services throughout a complete farming cycle via a single access point. This cumulative thesis comprises five original, peer-reviewed scientific papers, whose purpose is to explore the aforementioned fundamental objective of designing and implementing a digital platform that enables smallholder farmers to access all essential services under one roof. Using DSR methodology, this study was systematically organized in six main stages. The first stage (Article 1) involved problem identification and requirements, during which we conducted a systematic literature review on digital technologies in agriculture and their adoption for sustainable agriculture globally and in Tanzania. The review assessed the challenges faced by smallholder farmers that require digital interventions in small and medium-income countries, with a case study of Tanzania. It was found that smallholder farmers need access to credit and insurance services, quality farm inputs, agricultural information, subsidies, government services, and market services to adopt sustainable farming practices.

In the second stage (Article 2), we developed an abstract design for an FDIS as a solution to enhance smallholder farmers' access to services identified in the first stage. FDIS is a comprehensive digital platform designed to integrate various service modules, bringing together all key agricultural stakeholders. These module services include farmers' data, agro-dealers, farm inputs, advisory, and market services. This design is based on the ICT4D theory, which posits that technology advancements should have a positive impact on people's lives by developing solutions that work effectively within the local context, rather than simply copying and pasting technology from other contexts, such as from developed to developing countries. FDIS is centered around data management and data sharing among stakeholders for service exchanges. Theoretical application of the FDIS platform could help resolve farmers' challenges by ensuring access to credit and insurance services, tailored advisory and extension services, input delivery, subsidies, and predicting various market prices for their use. It enables farmers to connect with the market, ensuring transparency in transactions.

We conducted a survey in the third stage (Article 3) to present the designed digital artifact solution to key stakeholders and collect their opinions for an improved design. The survey provided an insight into the status of digital technologies adoption in Tanzania and the impact of the proposed FDIS platform on sustainable agriculture among smallholder farmers. Stage four (Article 4) involved developing a concrete design based on the opinions of key agricultural stakeholders in Tanzania. A few additional services were incorporated into a refined artifact design to address challenges identified by stakeholders. Stage five (Article 5) provided a proof of concept of the system using Android Studio, Iguana, and the Flutter Framework. We provided part of the FDIS services, which include farm and farmer data modules, financial modules, advisory and market modules, for presentation and demonstration purposes. Stage six involves evaluating the system, where stakeholders and developers collaborate iteratively to refine the system for actual use. The proof of concept (stage five) and evaluation (stage six) follow an agile process (design, develop, test, deploy, and review) to ensure the system meets the requirements and needs of the stakeholders.

8.2 Research Questions Review

This thesis was guided by four research questions formulated to answer the main research question and achieve the general research objectives. Therefore, this section presents the answers to the research questions posed in the study.

1. What are the common challenges facing smallholder farmers, and what services are needed for a complete farming cycle? **(RQ1)**

   We conducted an extensive literature review to assess (1) digital technologies and sustainable agriculture, (2) the availability of digital technologies to smallholder farmers, and (3) the challenges of smallholder farmers towards the adoption of sustainable agriculture. **The advanced digital technology in agriculture, mostly used by large-scale farmers, significantly contributes to sustainable agriculture. However, the existing digital services for smallholder farmers lack sustainability in the agricultural context and fail to meet the comprehensive needs of services throughout the entire farming cycle. In most developing countries, Tanzania included, digital technology and services respond to a challenge at a particular stage of the farming process or to a specific value chain.** Based on this literature review, we identify inequalities between large and small farmers, as well as environmental challenges associated with ICT itself.
2. What digital platform could be designed and implemented to address the challenges of the smallholder farmers in Tanzania? **(RQ2)**

   After identifying common challenges faced by smallholder farmers in adopting sustainable agriculture, we designed a digital platform that enables smallholder farmers to access all essential services (subsidies, credit, insurance, government services, market information, and farming information) under one roof. **Proposing a state-owned (or public-private) FDIS framework. FDIS is a data management framework that brings together key stakeholders in agriculture to improve the sustainability of services, monitor various practices, and provide a single point of access to essential services, including credit and insurance, subsidies, quality farm inputs, market access, and advisory services.** The framework provides a single point of access to several essential actors: farmers, financial institutions, farm product consumers, agro-dealers, government agencies, and processing industries.
3. What is the applicability of the designed digital framework in addressing the existing challenges faced by smallholder farmers in Tanzania? **(RQ3)**

   We used four case illustrations from Tanzania to demonstrate the applicability of the designed digital framework in addressing common challenges faced by smallholder farmers. **The illustrations revealed farmers' and other stakeholders' access to quality farm inputs through agro-dealers, subsidies, and distribution of financial and market services. Moreover, we provided a proof of concept of FDIS and demonstrated its applicability in providing advisory services, as well as financial and market services,**

to all stakeholders. Indeed, FDIS demonstrated the ability to address the common challenges faced by smallholder farmers, promising a path to sustainable agriculture.

4. What are the prerequisite infrastructures and other capabilities and resources for such a framework to be successfully implemented and sustainably operated? **(RQ4).**

   Apart from the ICT infrastructure, we discussed other critical factors for consideration in the successful and sustainable implementation of the FDIS platform. These include issues related to data, such as data ownership and sovereignty, legal issues on data protection, and data quality. Other discussed complementary investments are good policy, an education system, stable electricity service, and a skilled workforce, which are essential for the sustainability and maximum impact of ICT projects.

Table 15. Summary of published work and scientific contribution

	Article 1	Article 2	Article 3	Article 4	Article 5
Research Focus	To identify common challenges of the smallholder farmers and assess digital technologies and sustainable agriculture	Designing a digital artifact that solves the common challenges of smallholder farmers in a complete farming cycle	Understanding the state of e-Government agricultural services toward proposing a new digital solution	A refined digital artifact based on stakeholders' opinions	Implement part of FDIS and demonstrate its applicability in the real-world
Paper Title	Digital Technology and Services for Sustainable Agriculture in Tanzania: A Literature Review	Data management system for sustainable agriculture among smallholder farmers in Tanzania: research-in-progress	State of Agricultural E-Government Services to Farmers in Tanzania: Toward the Participatory Design of a Farmers Digital Information System (FDIS)	Designing a farmers digital information system for sustainable agriculture: The perspective of Tanzanian agricultural stakeholders	A Farmers' Digital Information System (FDIS) for Sustainable Agriculture Among Smallholder Farmers in Tanzania
Authors	**Gilbert E. Mushi**, Giovanna Di Marzo Serugendo, and Pierre-Yves Burgi	**Gilbert E. Mushi**, Giovanna Di Marzo Serugendo, and Pierre-Yves Burgi	**Gilbert E. Mushi**, Pierre-Yves Burgi and Giovanna Di Marzo Serugendo	**Gilbert E. Mushi**, Pierre-Yves Burgi and Giovanna Di Marzo Serugendo	**Gilbert E. Mushi**, Aaron Andrew Mwakifamba Pierre-Yves Burgi and Giovanna Di Marzo Serugendo
Methodology	A systematic review using PRISMA guidelines	Design Science Research	Survey research	Design Science Research	Design Science Research
Scientific Contribution type	Empirical findings	Empirical findings: abstract FDIS design	Empirical findings	Empirical findings: concrete FDIS design	Empirical findings
Published Peer-reviewed Journal	Sustainability journal by MDPI (IF:3.6)	Information Technology for Development by Taylor & Francis (IF: 5.1)	Agriculture journal by journal by MDPI (Impact Factor 3.5)	The electronic journal of information systems in developing countries by Wiley (IF:1.1)	Information journal by MDPI (IF: 2.6)
Status	Published	Published	Published	Published	Published
Author Contributions	**Contribution of the PhD Candidate 90%:** Writing the paper-original draft, G.E.M., data collection and analysis, G.E.M.; writing—review and editing, P.-Y.B. and G.D.M.S.; supervision, G.D.M.S. and P.-Y.B.	**Contribution of the PhD Candidate 90%**: Writing the paper—original draft, G.E.M., data collection and analysis, G.E.M.; writing—review and editing, P.-Y.B. and G.D.M.S.; supervision, G.D.M.S. and P.-Y.B.	**Contribution of the PhD Candidate 90%**: Writing the paper—original draft, G.E.M., data collection and analysis, G.E.M.; writing—review and editing, P.-Y.B. and G.D.M.S.; supervision, G.D.M.S. and P.-Y.B.; funding acquisition, G.E.M.	**Contribution of the PhD Candidate 90%**: Writing the paper—original draft, G.E.M., data collection and analysis, G.E.M.; writing—review and editing, P.-Y.B. and G.D.M.S.; supervision, G.D.M.S. and P.-Y.B.	**Contribution of the PhD Candidate 70%**: Writing the paper—original draft, G.E.M., software, A.A.M.; writing—review and editing, P.-Y.B. and G.D.M.S.; supervision, G.D.M.S. and P.-Y.B.

8.3 Limitation of the study

This thesis aimed to design and implement a digital solution to address the everyday challenges faced by smallholder farmers throughout their entire farming cycle. The emphasis is on the participation of smallholder farmers in sustainable agriculture. Indeed, it focuses on solving real-world problems in the agricultural sector of most low- and middle-income countries. While large-scale farmers (mainly in the global north) use advanced digital technologies for sustainable agriculture, the existing digital technologies for smallholder farmers (mainly in the global South) hardly meet their needs for sustainable agriculture. Nonetheless, the advanced digital technologies used in the global north cannot be copied and pasted to the global south. Therefore, digital solutions should be developed in the context in which they impact people's lives, without copying and pasting theories and technologies created in the so-called developed countries to developing countries. The main contribution of this thesis is the design and proof of concept of a digital platform that addresses common challenges faced by smallholder farmers throughout their entire farming cycle, promoting sustainable agriculture. However, there are several limitations to this thesis, explained below as follows:

- **Lack of real-world data**: FDIS is a data-driven information system that collects, organizes, and allows sharing of data among different stakeholders for service exchange. Although we provided a proof of concept of the FDIS platform, we were unable to demonstrate it using real-world data, such as the data from farms and farmers shown in Table 13.
- **Integration and interoperability**: We emphasized that the FDIS platform should be integrated and interoperable to allow communication with the existing and new systems. This aims to leverage existing resources and enhance collaboration among key agricultural stakeholders. This thesis was limited to testing FDIS integration and interoperability.
- **ICT infrastructure dependence**: FDIS is a purely digital solution that relies heavily on a well-established ICT infrastructure. However, the ICT infrastructure of most low- and middle-income countries lags. For instance, during the survey conducted for this thesis in various rural areas of Tanzania, a lack of network coverage was observed in many villages. Moreover, FDIS is designed to operate only on advanced mobile devices such as smartphones, tablets, and computers. Despite the high penetration of smartphone usage in developing countries, most farmers in rural areas lack access to these devices and the ability to use them effectively.

- **Digital literacy**: This thesis aimed to design and develop a digital solution for the smallholder farmers, most of whom reside in rural areas of low and middle-income countries. The survey conducted in Tanzania by this thesis revealed that most farmers have low digital literacy. This can highly limit the potential of the envisaged FDIS platform despite their willingness to acquire digital skills.
- **Electricity and internet services**: Tanzania, like many other countries in the global South, has limited access to electricity and internet services. The FDIS platform operates on digital devices that require electricity and internet access. Although many rural areas are electrified, power instability and inadequate network coverage are significant limitations to the proposed digital solution.

8.4 Future Work

This thesis contributes to the body of knowledge with a digital solution that enables smallholder farmers to participate in sustainable agriculture. It further encourages the digitization of the agriculture sector as it brings together all key stakeholders, including the government. Despite these promising outcomes, the following areas warrant further investigation in the future.

- **Real-world implementation and testing of the FDIS platform**. This thesis validated the applicability of FDIS through the illustration of real cases in the agriculture sector and demonstrated the implemented part of the system. Indeed, FDIS presented a solution to the common challenges faced by smallholder farmers, promising sustainable agriculture. However, we recommend the real-world implementation and testing of the FDIS platform to explore further the real challenges of implementing and sustainably operating the envisaged platform.
- **Change management**. The use of the new platform requires behavioral studies focusing on change management, particularly stakeholders' adoption, and use of the platform. This explores how stakeholders are adopting and using the platform. Research on change management could play a significant role in identifying and responding to key issues such as digital illiteracy, governance, and user satisfaction.
- **Integrating FDIS with advanced digital technologies**. FDIS is designed and implemented in the context of smallholder farmers' environments. It does not copy and paste advanced digital technologies for sustainable agriculture, which requires enormous upfront cost and expertise. However, FDIS could benefit from incorporating advanced digital technologies, such as AI, robotics, and the IoT, to enhance precision agriculture. Integrating AI could enhance advanced FDIS functionalities, including yield

prediction or any other AI improvement, such as facilitating the interaction with the farmers through Large Language Models (LLMs).

- **Evaluating the impact of FDIS on smallholder farmers' productivity, income, environmental, social, and cultural sustainability**. FDIS is expected to make the agriculture sector more dynamic and sustainable by changing most agricultural value chains. These changes are expected to contribute to social and cultural sustainability due to increased productivity and income for farmers while preserving the environment.
- **Extending FDIS in the context of other countries**. FDIS has been developed in the context of the Tanzanian agricultural system, which is similar to that of many other developing countries. Therefore, future research could focus on examining the scalability of the FDIS platform in various countries.

This thesis contributes to the body of knowledge by presenting an information system based on data management that enables smallholder farmers to engage in sustainable agriculture without relying on advanced digital technologies that require substantial upfront costs and specialized expertise. The designed and implemented system addresses common challenges faced by smallholder farmers, particularly access to financial services, subsidies, quality farm inputs, logistics, advisory services, and market services, all under one roof. We hope that this contribution can transform existing agricultural value chains, making the farm sector more dynamic and sustainable.

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Appendices

Appendix A

Article I: Digital Technology and Services for Sustainable Agriculture in Tanzania: A Literature Review.

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Review

Digital Technology and Services for Sustainable Agriculture in Tanzania: A Literature Review

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Abstract: Digital technology has the potential to eradicate extreme poverty and food insecurity to the majority of smallholder farmers in the world. This paper aims to identify knowledge gaps on digital technology for sustainable agriculture and assess their availability to smallholder farmers worldwide. The particular case of Tanzania receives special attention. We conducted an extensive literature search from relevant databases for review. The advanced digital technology in agriculture, mostly used by large scale farmers, significantly contributes to sustainable agriculture. However, the existing digital services for smallholder farmers lack sustainability in the agriculture context and hardly meet the needs for a comprehensive set of services in a complete farming cycle. In most developing countries, Tanzania case included, digital technology and services respond to a challenge at a particular stage of the farming process or to a specific value chain. Based on this literature review, we identify inequalities among large and small farmers, as well as environmental challenges caused by ICT itself. To conclude we provide suggestions for improvements for smallholder farmers: developing a digital platform that addresses smallholder farmers' challenges in a complete farming cycle, bringing together the stakeholders at a country level, in order to achieve sustainable agriculture and support adoption of cutting-edge digital technology. These suggestions will be the starting point for future research.

Keywords: digital technology; sustainable agriculture; smallholder farmers; ICTs services; precision agriculture; smart farming; farmers services; Tanzania

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1. Introduction

The application of digital technologies in agriculture may eradicate extreme poverty and hunger in a yet constantly growing population—from 2019 to 2050 the population will increase by 2 billion people [1]. In recent years, digitization has changed the way the society performs its social-economic activities particularly due to increased interconnections through the internet and affordable digital devices creating a global digital ecosystem [2]. Digitization is increasingly becoming an essential tool of production, business and services to recover the society from unexpected novel corona virus pandemic that has brought devastating impact on the social, economic and environmental aspects [3]. The use of digital technology has proved useful in various sectors worldwide, such as Malaysian industries [4], healthcare [5] or manufacturing [3]. In the agriculture sector, digital technology has increased profitability, enhanced the quality of the products and somehow preserved the environment [6]. The current "Industry 4.0 digital transformations" apply advanced technology in the agricultural field for a more precise and real-time decision making in farming activities [7]. This new era of digital technology in agriculture uses knowledge from different disciplines, which include information science, computer and software engineering, environmental science, remote sensing, geographical positioning systems (GIS), crop and soil science and global positioning systems (GPS) [8]. The farm management system uses modern technologies such as artificial intelligence (AI), sensors, the Internet of Things (IoT), satellite images to collect data, big data and machine learning, contributing to higher productivity and profitability in this sector [6].

However, most small and medium-sized farmers cannot afford to adopt such modern technology for sustainable agriculture, which is contrary to the United Nations Sustainable Development Goals (SDG) principle of "leaving no one behind" [9]. Smallholder farmers generate enormous employment and income worldwide while producing over 70% of the world's food needs [10]. In Tanzania, the agriculture sector is the backbone of the economy with 26.7% of the GDP, employing more than 80% of the population, and women constitute 60% of the farm workforce [11,12].

Many scientists and organizations have used different approaches to enable digital technology by smallholder farmers to increase productivity and income. Efforts include developing mobile and online services that allow smallholder farmers to access various services such as weather information, farming information and knowledge, market information, and reliable buyers for their products [13,14]. According to Boyera and Grewal [15], and Gray et al. [16], digital technology and digital farmers profiling platforms for smallholder farmers could help farmers access essential services and improve productivity. However, despite all those efforts, the sustainability of these projects remains a significant challenge for achieving sustainable agriculture [10]. Furthermore, the application of digital technology requires the study of the value chain to meet the needs of services in the context of the farmer ecosystem.

This paper is part of a larger research project to harness digital technology for sustainable agriculture in Tanzania, which aims to identify knowledge gaps on digital technology and services available to smallholder farmers and sustainability in agriculture. Moreover, it suggests digital solutions for smallholder farmers towards sustainable agriculture in developing countries. The subject aligns with the United Nations SDGs, such as eradicating poverty and hunger, sustainable cities and communities, climate action and reducing inequality [9]. Developing new digital comprehensive artifacts could solve the existing problems of digital exclusion of smallholder farmers, such as access to credit, farming knowledge, farm inputs, government services and control, and the market for their products [17–20]. Responsible agriculture actors could adopt the artifact according to their country context. Therefore, this review addresses the following questions:

1. What digital technology and services are available to support the agriculture sector?
2. What is the relationship between digital technology and sustainable agriculture? How do smallholder farmers fit in?
3. What is the state-of-the-art use of digital technology and services by smallholder farmers in Tanzania?
4. What challenges need to be addressed in relation to the above questions?

The last question concerns the future research agenda and will be further developed in a subsequent publication. In this paper we focused on digital technologies and services in agriculture, with a specific emphasis on smallholder farmers and sustainability.

We organized this paper as follows. Section 2 describes the authors' methods to select papers for this review. Section 3 reviews related works that answer the above first three questions, which guides this review. Section 4 responds to the fourth question; it analyzes and synthesizes gaps regarding the availability of digital technologies and sustainable agriculture (as defined in this paper) to smallholder farmers. Section 5 concludes with a summary of the review and suggests future work.

2. Research Methods

We used PRISMA guideline in this study [21], which is a standard protocol and an evidence-based framework for doing systematic review studies. We conducted an extensive literature search based on a complex query in the Web of Science (WoS), IEEE Xplore and related databases (Food and Agriculture Organization, Google Scholar and

Research4Life). The aim was to find and review the latest literature in digital technology and sustainable agriculture in relation to smallholder farmers. The researchers combined the following keywords using the Boolean operators ("AND" and "OR") and parentheses during the search: digital technology, ICT services, smart farming, precision agriculture, digital farmer profiling, smallholder farmers and sustainable agriculture. The final search string was "('digital technology' OR 'ICT services' OR 'precision agriculture' OR 'smart farming' OR 'digital farmer profiling') AND 'sustainable agriculture' AND 'smallholder farmers'". However, the search string could not yield good results to FAO database due to type and differences in functionality. We conducted a search in October and November 2021, obtained and imported a total number of 1981 articles to Mendeley Desktop reference manager software (https://www.mendeley.com, accessed on 4 October 2021).

We applied exclusion criteria to the obtained results to identify relevant papers in digital technology, smallholder farmers and sustainable agriculture. We restricted the obtained results to the year of publication from 2015 to 2021 to get the latest articles in the subject area. We filtered out duplicated papers (using duplicate function in Mendeley software), articles without full text and not written in English. The inclusion criteria were as follows: (i) modern digital technologies in agriculture (e.g., smart farming, digital farmer services) including the sustainability components (economic, environmental and sustainability of the ICTs infrastructure and resources) and (ii) availability of the technology to smallholder farmers. Finally, we selected a total of 36 articles: 24 articles on global literature (21 for recent digital technologies and sustainable agriculture, three on general digital service platforms developed for smallholder farmers) and 12 for the Tanzanian case.

We separately searched the literature in the Tanzanian case in local repositories (Sokoine University of Agriculture Institutional Repository), WoS and Google Scholar. In this search, we did not limit the literature by the year of publication to obtain more detailed background information in the country's ICTs and smallholder farmers' services. We obtained 18 articles from local repositories for analysis as the result of the complex query "digital technology" OR "ICT services" AND "smallholder farmers" OR "agriculture" AND "Tanzania". We selected 12 articles for the review after filtering five articles which were similar to articles from Google Scholar and WoS, (see Table 1).

Table 1. Reviewed literature under PRISMA guideline.

Search Category	Identification		Screening		Included
General literature	Records identified from databases (N = 1981)	Duplicate removed (N = 85)	Records screened (N = 1687)	Records excluded (N = 1581)	Studies included in review (N = 24)
		Removed for other reasons (N = 209)	Reports sought for retrieval (N = 106)	Reports not retrieved (N = 11)	
			Reports assessed for eligibility (N = 95)	Reports excluded by the study criteria (N = 71)	
Tanzanian case	Records identified from databases (N = 18)	Duplicate removed (N = 5)	Records screened (N = 13)	Records excluded (N = 1)	Studies included in review (N = 12)
		Removed for other reasons (N = 0)	Reports sought for retrieval (N = 12)	Reports not retrieved (N = 0)	
			Reports assessed for eligibility (N = 12)	Reports excluded by the study criteria (N = 0)	

3. Results

We present the results of this paper in response to the research questions. First, the results of the digital technology and services available to support the agriculture sector worldwide. Second, the results of the relationships between digital technology and sustainable agriculture, focusing on smallholder farmers inclusion in digital transformation.

Furthermore, we re-defined sustainable agriculture in the context of this paper to address the identified gaps in existing literature. Finally, the results of the Tanzania case current status in the use of digital technologies in agriculture and challenges towards sustainable agriculture.

3.1. Digital Technology and Services in Agriculture

For a long time, the agriculture sector has embraced new technologies to increase production and profitability while improving the environment. The Organization for Economic Co-operation and Development (OECD) defines digital technologies as: "ICTs (information communication technologies), including the Internet, mobile technologies and devices, as well as data analytics used to improve the generation, collection, exchange, aggregation, combination, analysis, access, searchability and presentation of digital content, including for the development of services and apps" [22].

Farmers use digital technologies in different domains of agriculture (summarized in Table 2). These domains include digital technology for farm management, financial services, market services, and farming knowledge and information services. Additionally, some digital platforms provide all essential services to farmers in the farming ecosystem. Many ICTs projects for farmers at the country level offer solutions to a particular farming problem, mainly for a specific value chain.

Table 2. A summary of digital services for farmers.

Services		Digital Artifact Solutions	Sources
Farm management	IoT	Sensors: Fixed position, UAV, Satellites, UGV	[23–27]
	Data Management and Analysis	Farm Management Information Systems (FMIS)	[7,28,29]
	Decision-making and Variable Rate Technology	Variable rate nitrogen fertilizer (VRNF), CLAAS VRT, Automated yield monitoring system II (AYMS II), fuzzy logic DSS, AgroDSS	[30–33]
Financial services		Index-based agricultural insurance, AFPOH, M-Banking	[34–38]
Knowledge and information		Weather forecasts, pesticides, and fertilizer information; KALRO mobile applications, Farmers Advisory Systems	[39–41]
Market		eSoko, Tru Trade, E-Wallet Scheme, E-Krishok and Zero Hunger	[35,41–43]
e-Government		Online Fertilizer Recommendation System (OFRS) in Bangladesh, AFPOH in India, KALRO in Kenya	[35,40,44]
Profiling platform		Digital farmer profiling platform	[10,15,16]

Source: Author's compilation.

3.1.1. Farm Management

The current industry 4.0 digital transformation in agriculture integrates IoT, cyber-physical systems, AI, Big Data, Machine Learning and Cloud computing with agricultural machinery [45]. It is more common to precision agriculture whereby innovative ICT solutions and IoT components such as sensors monitor spatial and temporal variability in farm production [7,46]. Site-specific farm management provides an understanding of soil and crop characteristics unique to each field, thus enabling farmers to apply farm inputs (such as irrigation, fertilizers, pesticides and herbicides) in small portions where needed for the most economical production [47]. Controlled farm inputs increase farm productivity and profitability and conserve the environment, promoting sustainable agriculture development [48]. Precision agriculture and smart farming rely on data management to make valuable decisions. The embedded digital technology components can be categorized into three phases: (1) data collection (IoT), (2) data management and analysis, and (3) decision making and variable rate technology (actuation) [6].

Data Collection—IoT

IoT in agriculture uses sensors—devices used to collect data from the field for easy monitoring of the crops and other digital tools to collect essential data for profitable decision-making in farming [6]. The sensors are mounted in the mobile farm machinery or fixed in the field, such as a local weather station. For instance, Kilin [23], used a network of automated stations in the vineyards to detect areas affected by pathogens for site-specific application of pesticides. The stations collect real-time data such as airborne particles, temperature and relative humidity of the air and soil, solar irradiance, spores, and leaf humidity. AI is then used to analyze the spatio-temporal heterogeneity data based on optical particle counters (OPC) to identify areas affected by the pathogen (i.e., *Plasmopara viticola*) [23]. The results allow farmers to apply pesticides in specific field zones leading to cost-effective, healthy products and environmentally friendly farming practices. Saiz-Rubio [6], classified sensors into three: remote sensing, aircraft, and proximal sensing. Remote sensing, most often satellites, has been an essential tool for collecting field data in smart farming. The satellites used to provide agricultural data include WorldView 2 and WorldView 3 multispectral satellite sensors using Normalized Different Vegetation Index (NDVI) standard [24,49]. Furthermore, the European Sentinel 2 satellite system, which gives access to 10 m 4-band multispectral data for "NDVI imagery of soil and water, covers the Earth every 10 days; the American Landsat satellites provide spectral data from the Earth each 16 to 18 days" [6,49].

Aircraft sensing, usually "remotely-piloted aircraft (RPA) and unmanned aerial vehicles (UAV)" such as drones, capture field data at a closer distance of up to 100 m, contrary to the order of 700 km of satellites [2]. Although aircraft sensing is expensive and requires high skills to generate quality field data, they are flexible and reach field areas where other equipment cannot. Proximal sensing is the latest technology based on "autonomous ground systems", promising new agriculture transformation [2]. According to Saiz-Rubio [2], in comparison to remote and aircraft sensing, proximal sensing monitors the crop in the ground at less than 2 m between a crop scanned and sensor. The payload of sensors is placed in ground vehicles that move around the field to collect accurate and quality data from the crops. Proximal sensing allows a real-time application, such as applying fertilizer where needed and spraying herbicides and pesticides where weeds or pests have been detected [25].

Robotic technology in farming is another area of interest and part of proximal sensing where unmanned ground vehicles (UGV) collect data and manage various farm activities [26]. The farmers use UGVs for soil analysis, seeding, transplanting, harvesting and crop scouting. Thus, UGVs allow a continuous field data collection process to monitor crop status and growth conditions [50]. VineRobot and Vinescount, funded by the European Commission, are examples of robotic technologies in smart farming that monitors vineyards by collecting data from the vines' canopy and creating water and nutrition status maps [6]. Industries manufacturing agricultural tools are also producing scouting robots. For example, Rowbot Systems LLC of USA introduced a multitask robotic platform to map crop growth zones, apply fertilizer and other related tasks [27]. Another example is the robot Oz the autonomous weeding and seeding [51].

Data Management and Analysis

A digital system receives data from different IoT devices and helps generate meaningful information for production. Large scale and commercial farmers use farm management information systems (FMIS) to acquire data, store, analyze and manipulate data in precision and smart farming. FMIS enables farmers to manage various farming activities from the initial planning stage to harvest and record important information of the performed activities [28]. Farmers can extract information such as field maps to determine crop and field conditions necessary for actions related to minimal use of resources, compliance with standards, and quality of agriculture production. There are different FMIS on the market (most are proprietary) with various features to manage farm generated data. The systems manage farm operations based on data acquired and processed automatically for planning, monitoring, supporting decision-making and keeping valuable records [29]. Hrustek [7], mentioned that FMIS records critical information, including "harvests and yields, profits and losses, farm task scheduling, weather prediction, soil nutrients transport and field mapping". A few examples of FMIS are ADAPT, Agrivi, Agroptima, Farmleap, owned mainly by companies from developed countries. More advanced FMIS provides early warning, financial management and integrates other actors such as input suppliers and product distributors.

Decision-Making and Variable Rate Applications

Farmers need to decide on the vast volume of collected data, considering different field parameters. Managing such complex data manually is difficult, time-consuming and possible for ineffective decision-making. [7]. Hrustek [7], added that farmers could use artificial intelligence (AI) and machine learning to support decision-making in agriculture through available big data. Wolfert [30], argued that agriculture has many areas for applying different AI technologies. For instance, Giusti and Marsili-Libelli [31] developed a decision support system (DSS) based on fuzzy logic to manage irrigation considering the soil characteristic and type of crop. Additionally, Bazzani [52] developed a decision-support system (DSS) that analyzes short- and long-term availability of water based on soil type, machinery and irrigation systems. Furthermore, Rupnik et al. [32], developed AgroDSS cloud-based DSS that allow farmers to upload data or integrate with FMIS through an application programming interface (API) to get different output decisions such as farm pest management.

The variable rate technology (VRT) has made it possible for the decision to be made autonomously. According to Hrustek [3], actuation is the execution of activities in the field following decision making from collected data. VRT includes robots used to perform different farm activities (farm preparation, planting, pest and weed control, fertilization, harvesting) previously conducted by human labor or conventional farm machines [24,31]. The variable-rate device receives commands from a computerized DSS. It performs various farming tasks such as applying fertilizer, pesticides and herbicides in the specific field zones where needed (real-time applications) and harvesting [53]. A few examples of VRT machines include the automated yield monitoring system II (AYMS II) made of unique "eye" color cameras and real-time kinematics-GPS for wild blueberry harvesting [54]. A sensor-based variable rate nitrogen fertilizer (VRNF) measures nitrogen with a multispectral sensor and fertilizer spreader mounted on a tractor, for real-time application conforming to the measured nitrogen in the crop [33]. The CLAAS VRT is used to apply nitrogen fertilizer, compatible with the "ISARIA" sensor [7]. VRT increases production and preserves ecological balance through efficient farm inputs, i.e., less crop fertilizer and chemicals [55]. Figure 1 presents the three main categories of smart farming data life cycle.

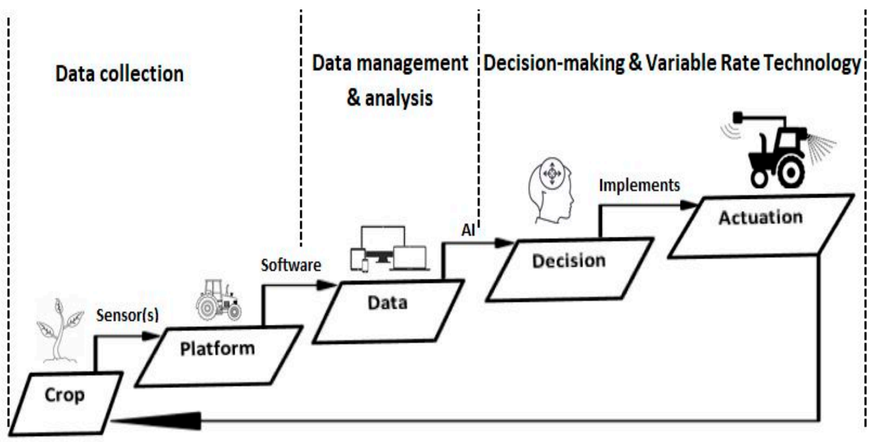

Figure 1. Smart farming data life cycle inspired by Saiz-Rubio and Rovira-Más [2].

3.1.2. Financial Services

Smallholder farmers face the challenge of access to financial services affecting agriculture production and income of many rural communities in developing countries [17]. Digital technology is an essential tool for improving access to finance and the commercialization of smallholder agriculture. A study on the awareness and use of m-banking (mobile banking) shows that most smallholder farmers in Kenya use the technology to access finance for agriculture-related activities [34]. Kirui [34], concluded that m-banking enables smallholder farmers to access investment capital for purchasing quality seeds, farm machinery, fertilizer and pesticides, leading to increased production and income. The Association for People of Haryana (AFPOH) is an ICT-based agriculture initiative in India that enables most smallholder farmers to access finance for improved agriculture [35]. Different countries embrace digital technology to allow the commercialization of smallholder agriculture as poverty alleviation and food security strategy.

Furthermore, agriculture insurance is an essential service for smallholder farmers. The farmers normally encounter various production and market risks which lower their income and ability to produce year after year. Hess and Hazell [36], mentioned natural disasters such as extreme droughts, floods, hurricanes and pest outbreaks are common risks for smallholders. The risks cause severe impacts in economic development which leads to extreme poverty. In the past, governments and organizations designed several insurances to help small farmers towards sustainable agriculture. However, agricultural stakeholder and organizations considers index-based agricultural insurance as more effective for smallholder farmers in developing countries [37,38]. Still, majority smallholder farmers particularly in Africa have no access to insurance. For instance, approximately 650,000 farmers have access to insurance in Africa out of around 40 million smallholder farmers in Sub-Saharan African alone. [36]. The current trend of climatic change requires financial investment for agriculture transformation, including increasing availability and access to credit and insurance by smallholder farmers [56].

3.1.3. Knowledge and Information Services

Dissemination of agriculture information and knowledge is a critical move towards improved farming. Most smallholder farmers lack farming information and knowledge, so they rely on friends, family, and experience, resulting in low production [57]. Access to data in a complete farming cycle, from farm preparations, inputs, finance, harvesting and market of the products, creates high value in the commercialization of smallholder agriculture. Ali et al. [39], examined the critical information needs of farmers in Pakistan and developed a digital solution to deliver weather forecasts, pesticides and fertilizer information. E-agriculture initiatives in India emphasize disseminating information to most rural smallholder farmers through ICT, including management information systems, knowledge management systems and expert systems [35]. Sanga et al. [58], developed an information dissemination system to enable smallholder farmers to access critical farming information and knowledge from experts, bridging the gap of extension services through ICT. Scientists and organizations have developed mobile applications to disseminate different crops and livestock information. For instance, Kenya Agricultural and Livestock Research Organization (KALRO) has produced more than fourteen mobile applications for crops and livestock to help farmers access information and adopt modern farming techniques for increased production [40].

3.1.4. Market Services

Most large scale farmers use advanced FMIS, which provide linkage to critical services, including the market [42]. For instance, we can mention the combination of different methodologies to design information integration in the Netherlands for information sharing that supports the food supply chain—a movement of food into various stages from farmers to consumers and movement of money paid for the food by the consumers back to the farmers via the same steps in the reverse direction [59]. Wolfert et al. [59] argue that big data in smart farming is appealing as farmers can either be part of the closed, proprietary systems or of an open, collaborative system. A proprietary system is a highly integrated system of stakeholders bounded by terms and conditions. In contrast, with "open, collaborative systems" farmers are free to choose any stakeholder as business partners in a food supply chain. In either of the two (closed or open) scenarios, the food supply system enables farmers to exchange information with other actors in a supply chain (two-way traffic), harnessing essential knowledge for production based on consumer needs and other factors in the supply chain.

Smallholder farmers face the challenge of market access for their products [42,60]. Intermediaries force farmers to sell their products at a low price, resulting in unprofitable production. Thanks to ICT, smallholder farmers can access market information and participate in better-paying agricultural production. Market access is one of the critical components in e-agriculture initiatives in India. Rural farmers are linked to the market and get fair prices, improving income and sustainable life [35]. ICT related cases in Africa include "eSoko" in Ghana, "Tru Trade" in Uganda and "mFarming" in Kenya, Ghana and Tanzania [43]. These programs address the challenge of access to market information and fair price for smallholder farmers' products.

Furthermore, Nigeria's "E-Wallet Scheme" enables smallholder farmers to access subsidized inputs through mobile phones. Meanwhile, "E-Krishok and Zero Hunger" in Bangladesh and "Farmes' Advisory Information System" in Tanzania provides extension services to farmers, mainly advising farmers on farm input products [41–43,58,61]. These and many other related efforts not included in this paper are promising ICT initiatives for smallholder farmers access to the market.

3.1.5. e-Government Services in Agriculture

Governments play a fundamental role in developing any economic sector, including agriculture. For a long time, most governments have provided various services in agriculture, most often through extension agents responsible for linking with farmers [62]. However, several limitations to using extension agents include the difficulty of reaching the many smallholder farmers scattered throughout the rural areas, the inability to deliver multiple agriculture services to farmers and the high involved costs [63]. Governments have a central role of monitoring, controlling and bringing together agricultural stakeholders for services deliverance at a single access point; thus, promoting digital technology for sustainable agriculture at a country level. OECD [22], mentioned that ICT promotes government transparency and accountability to the community. Therefore, e-government provides opportunities for the government to deliver multiple, coordinated and timely services under one roof through a network of agricultural actors. Ntaliani et al. [64] assessed the potential of e-government in the agricultural sector which suggests that government should use the e-government model to offer services to farmers and rural communities. The Indian government, through the ministry of agriculture, supports various ICT programs for smallholder farmers to access essential services such as farm inputs, financial services, subsidies and market for increased production and income [35].

3.1.6. Digital Farmer Profiling Platforms and Services

Apart from precision agriculture and smart farming, many ICT services provide isolated solutions packages to farmers' needs. Digital farmer profiling is a business model developed in the past few years to provide essential solutions to smallholder farmers' needs. The platform service manages farmers' data based on blockchain technology to allow farmers to share their data with other stakeholders (such as credit and insurance companies) [16]. Digital farmers profiling seems promising in service delivery to the smallholder farmers. Studies in Africa, Asia and Latin America show how digital farmers profiling enables smallholders to access essential services such as financial services and marketing of their products [10,15,65,66]. Service providers manage the data (for a fee) on behalf of other actors, including the farmers. Despite the long debate over who owns the data (between service providers and farmers), Grameen Foundation—as experienced experts in the farmer profiling platform business model, has stated that sustainability of the project is a significant challenge once the project fund ends [16]. In addition, Boyera and Grewal [15] concluded that each country and value in the crop or livestock chain would have its approach to implementing a farmer profiling platform.

3.2. Digital Technology and Sustainable Agriculture

According to Bhakta et al. [53], Giray and Catal [67], sustainable agriculture refers to agricultural practices that ensure long-term increased farm production and farmers' income while protecting the environment. Precision agriculture and smart farming present a high level of sustainability using the most cutting edge technology to control farm inputs such as fertilizers, irrigation, herbicides and pesticides [6]. Farmers apply farm inputs to only parts of the field that need, thus improving product quality, reducing input cost, increasing productivity, preserving the environment, and achieving economic and environmental sustainability [7,67]. Social sustainability in agriculture results from economic and ecological sustainability, whereby, refers to the availability of enough food for all people, animals, and plant species in the world [7]. Literature on sustainable agriculture mainly focuses on agricultural operations and business models for increased profit while minimizing the use of agrochemicals to promote a healthy environment and higher production quality. The new "fog computing model" is useful for a clean environment in smart agriculture. Unlike cloud computing, the fog computing model reduces carbon emissions through energy-efficient digital hardware and renewable energy resources since data are processed closer to where it is collected [68].

In addition to previous sustainability approaches, this paper focuses on the fundamental component of sustainable agriculture in the digital era: the sustainability of infrastructures and resources that support digital agriculture services for smallholder farmers. Thus, this paper categorizes sustainable agriculture into three main topics: (i) sustainability of the infrastructure and resources offering digital services, (ii) economic sustainability—long-term increased productivity and profitability, and (iii) environmental sustainability—conservation ecology and minimizing ICT pollution through green computing (Table 3).

Table 3. Sustainable agriculture.

Components	Definition/Meaning	Characteristics
ICTs Infrastructure and resources sustainability	The ability to maintain digital systems (hardware and software) and human resources (such as IT specialists, services providers and data collectors) for long-term services to farmers.	Regular maintenance Hardware replacement Software upgrades Budget for human resources and service providers Energy consumption Environmental impact of production and disposal of ICT hardware
Economic sustainability	Refers to a long-term increased farm production that eventually increases farmers' income.	Less input cost High production Good market price Increased farmers' income
Environmental sustainability	Refers to actions taken consistently for conservation ecology by minimizing harmful agriculture and ICTs' environmental impacts.	Less use of agrochemicals Use of fortified agrochemicals Use of renewable energy Energy-efficient hardware Use of recyclable hardware Less carbon emission from data centers

Source: Author's compilation.

The literature review provides current status digital technology for sustainable agriculture, services available for smallholder farmers and Tanzania's case. Most established digital services for smallholder farmers lack environmental sustainability and sustainability of the infrastructure and resources that support the services. Some of the services in developing countries propose charging farmers and other beneficiaries to achieve sustainability of the services. For instance, the farmer profiling platform business model suggests that service providers receive revenue through interest paid on credit by farmers, commission on farm inputs and fees charged from buyers of the farm produce [16]. Although the model may achieve sustainability of the digital services, the burden cost is primarily on farmers, limiting the economic sustainability of individual farmers and farmers' organizations. Table 4 presents the availability of general digital transformations and agriculture sustainability to smallholder farmers.

Table 4. Digital services, smallholder farmers and agriculture sustainability.

Literature			Availability to Smallholder Farmers	Digital Technology and Agriculture Sustainability			
				ICTs Infrastructure and Resources Sustainability	Economic Sustainability	Environmental Sustainability	
						Conservation Ecology	Green Computing
Digital technology for farm management	Data collection—IoT [6,23,26,44,49,50]		×	×	√	√	×
	Data management and analysis [7,29,45]		×	×	√	√	×
	DSS and VRT [25–27,30–32,51,53,69]		×	×	√	√	×
Digital farmer profiling platform	[10,15,16]		√	√ *	√ *	×	×
Agriculture sustainability	Economic sustainability [6–8,33,53,67]		×	×	√	√	×
	Environmental sustainability	Conservation ecology [6–8,33]	×	×	√	√	×
		Green computing [68]	×	×	√	√	√

Source: Author's Compilation. Note: √ (Addressed) √ * (Addressed with limitations) × (Not Addressed).

3.3. Digital Technology and Tanzanian Agriculture

The Tanzanian government has consistently supported smallholder farmers and the agriculture sector. Since the 1960s, the government introduced 16 National Agriculture Input Voucher Systems (NAIVS) for farmers to access and use modern farm inputs (seeds and fertilizers) through contracted agro-dealers for improved production and income [70]. However, due to lack of government control, cheating and fraud, contracted agro-dealers sell the subsidized inputs at full market price, leading to deficient programs' impact on farmers [71].

Indeed, since the adoption of ICTs in the national development plans in 2003, many ICTs related projects have been conducted to address various challenges in the agricultural sector. Generally, the target areas are agricultural information dissemination by agricultural research institutions (ARIs) and extension services to farmers and farmers organizations (FOs) [13,14]. The increased use of mobile technologies also triggered projects on mobile farm services such as Global System for Mobile Association (GSMA) "Mobile for Development" projects and mobile applications to support farmers in different value chains [14], mobile application for poultry farmers [72], and mobile decision support systems [73,74]. Furthermore, the design of farmers digital advisory service called "Ushauri" to provide access to context-specific information from extension agents increases capabilities in decision-making and adaptation to changing environments [75]. These digital services don't meet the needs of a farmer's entire ecosystem; nor are they sustainable, as some of the mentioned services don't exist due to lack of sustainability plans or because farmers do not use the service. Digital technology intervention could attenuate the challenges and improve smallholder farmers' access to services for increased production and income. Table 5 presents the summary of existing digital artifact solutions and services addressing some challenges of farmers in Tanzania.

Table 5. A summary of digital services to farmers in Tanzania.

Services	Problems	Digital Artifact Solutions	Sources
Financial	Lack of access to credit	None	[19,76]
Farm inputs	Counterfeit fertilizers, pesticides and herbicides	Agro-inputs Products Verification System (APVS) mobile application	[77]
Market	Access to market and market information	mFarming mobile service	[43,78]
Agriculture knowledge and information for decision making	Lack of information, farming knowledge and extension services	mAgri tracker GSMA Mobile for Development projects	[14]
		Android mobile application for poultry farmers	[72]
		A web and Mobile-Based Farmers' Advisory System for extension services	[41,58]
		A mobile Decision Support System for access to climatic information	[73]
		A mobile and web-based extension support system for horticulture farmers	[74]
		"Ushauri" digital advisory service	[75]

Source: Author's compilation.

Despite all the efforts, smallholder farmers in Tanzania still face many challenges in accessing services from other actors in a farmer ecosystem. Challenges include access to credit [19,76], substandard agricultural inputs from uncertified agro-dealers [77,79,80], unfair market prices due to the involvement of middlemen and lack of government oversight [14,60,81,82].

4. Discussion

This paper emphasized the digital technology and services in agriculture, focusing on the smallholder farmers' participation in sustainable agriculture. So far, similar to other sectors such as manufacturing industries, agriculture sector is undergoing major digital transformations through the application of cutting-edge digital technologies.

Inequalities: It is also important to note that digital transformations in agriculture are highly characterized by digital inequalities between large- and small-scale farmers, and between high-income and low-income countries. Governments, researchers, organizations and other stakeholders need to address factors leading to digital inequalities for smallholders to engage into sustainable agriculture. Sustainable agriculture by smallholder farmers require digital solutions for solving common challenges, which need strong commitment and collaboration among agricultural stakeholders at a country level, and then the adoption of advanced digital solutions such as precision technology.

Technology advancements create possibilities for solving many social-economic challenges that the world faces. Smart agriculture is the latest technology that uses the most advanced tools and software such as remote sensing, big data, IoT, information systems, AI, decision support system (DSS) and variable rate application (VRA) in farm management [6,7,53]. However, these digital advancements in agriculture are not equally available around the globe due to different social-economic factors. While developed countries are fast-moving in cutting-edge agricultural technologies (agriculture 4.0), developing countries are lagging, leading to low production and environmentally unfriendly practices [83,84]. Some of the developing countries are making steps towards precision agriculture. For instance, Bangladesh's online fertilizer recommendation system (OFRS) enables smallholder farmers to efficiently apply fertilizer for sustainable agriculture production [44]. A review study shows opportunities for adopting precision agriculture by smallholder farmers in Sub-Saharan Africa (SSA). Nevertheless, these technologies are mostly experimental and mainly used by large-scale commercial farms in few SSA countries [85].

ICT—an environmental concern: The uneven adoption of new technologies in agriculture affects more than one billion smallholder farmers worldwide, which the FAO considers the world's largest food producer by 70% [16]. Nonetheless, precision agriculture is challenged by the environmental sustainability issues caused by ICT. Therefore, green computing—"maximizing the efficiency of computing resources and minimizing environmental impact" [86], could be more useful to smallholder farmers due to its reduced costs and economic and environmental sustainability. The most established digital agriculture services have sustainability issues and exclude smallholder farmers.

Challenges: Despite the promising developments in technology, digital services in agriculture are yet to achieve complete sustainability. As the latest digital transformation, precision agriculture lacks the component of green computing, causing environmentally unfriendly practices. Precision agriculture is also poorly adopted by farmers, especially in developing countries, leaving most smallholder farmers behind in sustainable agriculture, in addition to the fact that, in general, small farms produce proportionally more greenhouse gas emissions than very large ones [87]. Furthermore, ICT infrastructure and resources sustainability are fundamental components for long-term agricultural production and profitability.

Profiling platform: A digital farmer profiling platform business model was recently designed to enable smallholder farmers' access to different services for increased production and income [10,15,16]. The model could achieve economic sustainability, but service providers charging smallholder farmers directly and indirectly for infrastructure and resources sustainability affect farmers' profit margins. Lack of government participation in the model could lead to unsolved smallholder farmers challenges to some countries where government, for example, should control market price and subsidies to targeted poor farming communities. Digital farmer profiling also lacks environmental sustainability components.

Summary: Many large-scale farmers such as commercial farmers, wholesalers, traders and exporters have long invested in the use of ICT with well-developed farm inputs and market functions. For instance, precision agriculture uses advanced technology such as farm management information systems (FMIS), social networks and other complex customer and farm management systems [42]. Therefore, large-scale farmers are not often confronted with the sustainability of ICT infrastructure and resources as they cooperate in the business plan for investment. Digital services for smallholder farmers usually are established by the stakeholders such as the government, donors, commercial service providers, scientists and public–private partnerships; thus, the modality requires a proper mechanism for sustaining the infrastructure and other resources supporting the services.

Furthermore, the literature places more emphasis on economic and less onenvironmental sustainability. Engineers should also prioritize green computing when developing digital services for ecological sustainability in agriculture. The current digital technology systems in smart farming use cloud computing model to manage voluminous data through data centers. However, the data centers are highly wasteful in terms of expenses, energy consumptions and carbon emissions [88]. Furthermore, ICT hardware has an immense effect on the environment throughout its life cycle. The manufacturing phase involves using rare earth metals extracted under unfavorable environmental practices, which causes water, soil and air pollution, with high energy consumption in the use phase and e-waste produced in the final phase [89]. The cloud computing model commonly used in precision agriculture has also an immense negative impact on the environment due to carbon emission from data centers that host massive data [68]. To achieve the component of environmental sustainability, engineers propose using energy-efficient hardware, using renewable energy such as solar and wind, recycling e-waste and designing new tools such as cooling systems and datacenters with minimal impact to the environment [86,89–91]. We acknowledge the environmental impact of solar panels in their production and disposal phases; however, our focus is on the usage phase.

5. Conclusions

5.1. Literature Summary

This article provides an overview of the current status of digital technology and services available in agriculture sector, their contribution to sustainable agriculture and relationship to smallholder farmers. The digital technology varies from simple mobile and web-based applications, mostly for smallholders to complex autonomous, information and cyber-physical systems used by large scale farmers. Digital transformation seems promising and changing all aspects of life in different disciplines, leading to new business models, services and products. The use of digital technology in agriculture may solve the challenge of food insecurity in yet a constant population increase in the world. The literature analysis has shown that sustainable agriculture is a reality through digital technology and services. However, the cutting-edge digital technology in agriculture (smart farming) is not accessible to smallholder farmers who, despite their small size, produce over 70% of the world's food. The existing digital models for smallholder farmers, including the Tanzanian case, lack vital components of sustainable agriculture. They mainly address the needs of smallholder farmers at a particular stage of a farming cycle, such as farm preparations. Furthermore, the services are primarily for a specific country and crop value chain; examples are Tanzania (Table 5) and Kenya's KALRO mobile applications for different crops and livestock.

We found that the literature relates sustainable agriculture more with the precision technology. However, is it always needed, especially real-time precision agriculture, or sustainability can be achieved with other means? For instance, smallholder farmers are often reluctant in adopting precision technology even in developed countries [92], where management differs greatly between large and small farms. Perhaps establishing advisory services specifically for smallholder farms can be more efficient than using precision technology that communicates directly with the producer. Indeed, we believe that if smallholder farmers can access financial services (credit and insurance), quality farm inputs, subsidies, advisory services and market, they can increase production and profitability, adhere to environmentally friendly farming practices hence sustainable agriculture. Therefore, organizing agriculture stakeholders (including the government) at a country level and developing digital solutions that address common challenges of smallholder farmers could lead to sustainable agriculture and adoption of precision farming in developing countries. The limitation of this study is emphasized in identifying smallholder challenges towards sustainable agriculture in Tanzania case and proposing digital solutions. The needs of smallholder farmers may differ among countries and could need a thorough study to adopt the proposed digital solutions in a particular country's context. Additionally, the study focused more in crop farming, thus, did not cover digital technologies used for instance in livestock management.

5.2. Towards a Comprehensive Digital Platform for Sustainable Agriculture in Smallholders Farms

In the future, we plan to design and implement a digital platform for smallholder farmers to access all essential services (subsidies, credit, insurance, government services, market and farming information) under one roof. The platform will address the needs of smallholder farmers in a complete farming cycle—from farm preparations, farm inputs, harvesting and post-harvesting activities by consolidating agriculture stakeholders at a country level. The platform will also adhere to all critical components of sustainable agriculture, namely the sustainability of digital infrastructure and resources offering the services, economic and environmental sustainability.

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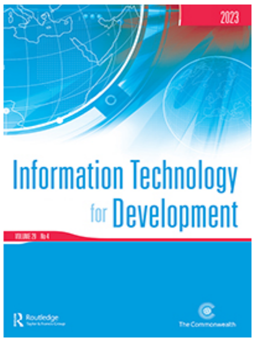
Appendix B

Article II: Data management system for sustainable agriculture among smallholder farmers in Tanzania: Research-in-progress.



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Data management system for sustainable agriculture among smallholder farmers in Tanzania: research-in-progress

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ABSTRACT

Smallholder farmers produce about 70% of the world's food and employ more than one billion people. They therefore have an important role to play in eradicating food insecurity and poverty among the world's growing population. Although there are different digital services for smallholder farmers, the existing services lack sustainability in the agriculture context and hardly meet their needs. Data management and sharing among different agriculture stakeholders has the potential to make agriculture sustainable, but there is a need to enable access to digital services in an entire farming cycle under one roof. This paper aims to propose the design of a comprehensive data management digital framework to solve common challenges of smallholder farmers in Tanzania and other countries' agricultural systems. We follow the design science research (DSR) method to develop an artifact that interacts with the problem context. To illustrate the framework's applicability, we use different case studies in Tanzania.

KEYWORDS

Smallholder farmers; information system design; sustainable agriculture; farm data management; Tanzania

1. Introduction

The world's food demand is expected to increase by 35%–56% between 2010 and 2050 (van Dijk et al., 2021). The Food and Agriculture Organization of the United Nations (FAO) predicts a much larger increase in demand of 70% over the same period (FAO, 2009). This demand, linked to the estimated world population increase between 9.4 and 10.2 billion people by 2050, with Sub-Saharan Africa leading the growth rate by 114% (FAO, 2009), calls for action to increase the production and well-being of the society despite many challenges such as decreasing arable land, climate change, increased water demand, and environmental pollution. The question of eradicating global hunger and extreme poverty – Sustainable Development Goals (United Nations, 2015) – remains a major global societal challenge. Investing in smallholder farmers has the potential to eradicate food insecurity and extreme poverty globally. According to FAO (2021), smallholder farmers produce 70% of the world's food and employ more than one billion people, the majority living in rural and semi-urban areas. Agriculture is the backbone of the national economy in Tanzania (as in many other developing countries), and more than 70% are smallholder farmers (Chandra & Collis, 2021). Thus, agriculture is essential to increase income and food security, hence the need

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for a common approach to agricultural development that would allow smallholder farmers to participate in agri-business (ITU, 2016).

In this digital age, Information Technology (IT) is central to the development of political, economic and social aspects of human life. Smallholder farmers can potentially achieve sustainable agriculture through Information and Communication Technologies (ICTs). Furthermore, ICTs can significantly reduce poverty vulnerability of smallholder farmers by increasing their income and ability to make more informed decisions on various nonagricultural and matters related to agribusiness (Zhang et al., 2022). According to Smidt and Jokonya (2021), the adoption to ICTs solutions to support smallholder farmers requires the collaboration of different actors, including the government to create a comprehensive localized framework. Enabling smallholder farmers' participation in agribusiness through digital technologies is critical to the socio-economic development of agriculture value chains (AVCs) within and outside the country. The development of digital solutions for smallholder farmers and a strong political will to include vulnerable and marginalized people (such as rural women, youth and indigenous communities) in this process is important for sustainable development in small and medium income countries (FAO, 2021; Smidt & Jokonya, 2021).

Despite available advanced digital technology and other ICTs-related efforts to help smallholder farmers access essential services for sustainable farming, such farmers still face many challenges. Large-scale and commercial farmers have long used digital technology in agriculture (e.g. precision and smart farming) to manage farm activities and access services in a complete farming cycle (USAID, 2013). Agriculture industries develop comprehensive digital agricultural solutions such as sensing technology for field data collection, farm management information systems (FMISs) for acquiring and analyzing data, decision support systems, and variable rate technology to actuate real-time decisions (Saiz-Rubio & Rovira-Más, 2020). These cyber-physical technologies are mainly designed for high-income countries and require a substantial financial investment. Furthermore, precision agriculture and smart farming have shown great potential for sustainable agriculture – increased production and income and environmental conservation (Bhakta et al., 2019; Giray & Catal, 2021). Few recent studies in developing countries report the possibilities for adopting precision farming technologies, but many are still experimental (Onyango et al., 2021). Most smallholder farmers can hardly afford this kind of ICTs solution for sustainable agriculture.

There are many ICTs solutions developed to address challenges in agriculture and smallholder farmers ranging from simple mobile applications to web-based digital platforms. To mention a few, the ICTs solutions on dissemination of agricultural information and advisory services to farmers through different channels such as telecentres and agricultural knowledge centers (Birke & Knierim, 2020; Mtega, 2021; Sanga et al., 2014); farmers adoption of e-market (Cloete & Doens, 2008); and mobile applications for different crop and livestock value chains (FAO, 2018; Shapa et al., 2021). Moreover, some government are developing and implementing ICTs project to solve smallholder farmers challenges such as e-governance mediated agriculture in India (Behera et al., 2015) and a fertilizer recommendation system in Bangladesh (Hossain & Siddique, 2020). However, the existing ICTs solutions for smallholder farmers particularly in developing countries address a specific challenge, which requires a farmer to coordinate various solutions to obtain services in a complete farming cycle.

Considering the above, this article aims to answer the following questions: (1) 'What comprehensive digital framework could be designed so that smallholder farmers can access all the essential services of a complete farming cycle via a single access point?' – to answer this question, it is necessary to identify the common challenges faced by smallholder farmers and the services needed for a complete farming cycle; (2) 'How does the designed digital framework contribute to sustainable agriculture and development?' (3) 'What is the applicability of the designed digital framework in solving the existing smallholder farmers' challenges in Tanzania?' (4) 'What are the prerequisite infrastructures and other capabilities and resources for such a framework to be successfully implemented and sustainably operated?'

This paper is part of a larger study that aims to design and implement a digital framework for smallholder farmers to access all essential services (subsidies, credit, insurance, government services, market, and farming information) under one roof. In a previous study (Mushi et al., 2022), we conducted a systematic literature review to identify common challenges of smallholder farmers with special attention in the Tanzanian case. According to Chandra and Collis (2021), the challenges identified in the Tanzanian case are more similar across developing countries. Therefore, the designed platform will potentially be helpful in many other developing countries. Such a platform could increase farm production and profitability while preserving the environment.

In this paper, we contribute to the field for IT for development by proposing a state-owned (or public-private) Farmers' Digital Information System (FDIS) framework. FDIS is a data management framework for development bringing together key stakeholders in agriculture to improve services' sustainability, monitoring various practices, and offering single access to essential services such as credit and insurance, subsidies, quality farm inputs, market, and advisory services. The framework provides such a single access to several essential actors: farmers, financial institutions, farm products consumers, agro-dealers, government agencies, and processing industries. We designed the FDIS framework for sustainable agriculture and illustrated its applicability through four case studies from Tanzania. We used the design science research method to develop the artifact solution for the common challenges of smallholder farmers in Tanzania. As part of the evaluation stage, we have shown the applicability of FDIS in solving smallholder farmers' problems such as access to subsidies, credit and insurance, quality farm inputs, and market services. In addition, we have illustrated the framework's viability in sustainable agriculture and development among smallholder farmers.

The main contribution of this paper is a proposed abstract design of the FDIS framework that integrates different modules (farmers' data, agro-dealers, farm inputs, advisory and market data module). We structured this paper into seven sections. Section 2 provides the theoretical framework of key IT for agriculture sector development; Section 3 describes the research methodology we applied to design the artifact solution; Section 4 presents the results of the study that covers different modules of the FDIS framework; Section 5 illustrates the FDIS framework applicability in four different Tanzanian cases; Section 6 discusses various issues related to the FDIS framework implementation, contribution to sustainable agriculture and development; finally, Section 7 concludes this paper with a summary of the artifact and future work.

2. Theoretical background

This section provides the theoretical background of our study, focusing on the key IT for agriculture sector development. It follows the theories of Information and Communication Technology for Development (ICT4D) by Qureshi (2015) and Zheng et al. (2018), in the sense that technological advancement should have an impact on people's lives, without copying and pasting theories and technologies created in the so-called 'developed countries' to 'developing countries.' By reviewing the literature, we identify cutting-edge ICTs in agriculture, ICTs used in small and medium income countries and specifically in the agriculture sector in Tanzania.

2.1 Modern ICTs in agriculture

Globally, precision agriculture (evolving to smart farming) is the leading cutting-edge digital solution that meets the needs of farmers in a complete farming cycle. It involves the use of sophisticated technologies such as the internet of things (IoT), farm information management systems (FIMs), artificial intelligence (AI), decision support systems (DSS), and variable rate applications or actuators (Saiz-Rubio & Rovira-Más, 2020). These components work autonomously to optimize farm input and yield forecasts and collaborate with other stakeholders such as services providers and the market, thereby improving sustainability in agriculture. In the Global North, digital farming platforms are usually owned by private companies that farmers and other stakeholders can subscribe to, normally for a fee. While these advanced digital platforms may not be applicable to developing countries (for example 365FarmNet, 2022), aspects such as the ability to record data even without Internet access and data protection strategies could be useful for platforms being considered in the developing world.

Indeed, precision agriculture requires a substantial capital investment that smallholders can hardly afford. Therefore, in recent years, scientists and organizations developed a digital farmer profiling platform to enable smallholder farmers to access essential services in a complete farming cycle (Boyera et al., 2017; Gray et al., 2018). Service providers manage farmers' profiles for a fee paid by stakeholders, including farmers, to maintain the farmer profiling infrastructure. Stakeholders, such as financial institutions, automatically add fees to loans, which eventually affects the economy of smallholders. Such a digital profiling solution is still in the experimental stage and faces sustainability issues (Gray et al., 2018).

2.2 ICTs in lower and middle-income countries agriculture sector

Many digital agricultural solutions have been developed in low- and middle-income countries, which cover many aspects of socio-economic development of farmers. They include strengthening market of agricultural products through e-market (Cloete & Doens, 2008), improving agricultural extension services (Namyenya et al., 2021; Sanga et al., 2014), and disseminating agricultural information for improved farming and decision making (Bello-Bravo et al., 2020; Krell et al., 2021; Maredia et al., 2018; Mtega, 2021). These solutions alleviate several challenges faced by farmers such as fighting counterfeit farm inputs (Shao & Edward, 2014), access to financial services and mobile payment (Kinuthia & Mabaya, 2017; Kirui et al., 2010; Wenner et al., 2018) and access to farm insurance (Osumba et al., 2020).

The adoption of precision agriculture by smallholder farmers in developing countries offers a promising future, but as already pointed out, these advanced IT projects are still in their infancy (Onyango et al., 2021). Also, each country has various digital services for smallholder farmers ranging from simple mobile applications to Web-based digital solutions, for instance: the Association for People of Haryana's (AFPOH) e-governance mediated agriculture project in India (Behera et al., 2015), the Kenyan Agriculture and Livestock Research Organization's (KALRO) mobile applications project for different value chains (FAO, 2018), and the online fertilizer recommendation to farmers in Bangladesh (Hossain & Siddique, 2020). The digital solutions in developing countries have sustainability issues and generally solve a specific farming problem or value chain. Thus, a digital framework solution for smallholder farmers that resolve common challenges in a complete farming cycle through single access point is lacking. Such a digital framework will contribute to the development of farmers economically through increased production and income and strengthen agricultural value chains in developing countries.

2.3 ICTs and Tanzania agriculture sector

Since the adoption of ICTs in national development plans in 2003 (United Republic of Tanzania, 2003), Tanzania, like many other developing countries, has had various digital solutions addressing different farmers' challenges in different value chains, such as advisory services to farmers on various farming activities (Ortiz-Crespo et al., 2021; Sanga et al., 2013), access to market and market information (Hamill, 2017; Magesa et al., 2014) and combating substandard farm inputs (Shao & Edward, 2014) to ensure quality input for increased production and income. Many of these and other emerging digital solutions in agriculture operates in mobile application, influenced by high penetration of mobile devices (i.e smartphones) and Internet access.

Despite the existing digital solutions, smallholder farmers in Tanzania still face numerous challenges. These include poor access to subsidies (Masinjila & Lewis, 2018) and financial services (credit and insurance) (Kimaro, 2020), middlemen market disruption (Misaki et al., 2016; Navuri, 2018), substandard farm inputs (Shao & Edward, 2014), poor government control, and lack of personalized farming advisory and information services (Chandra & Collis, 2021). Figure 1 shows the existing

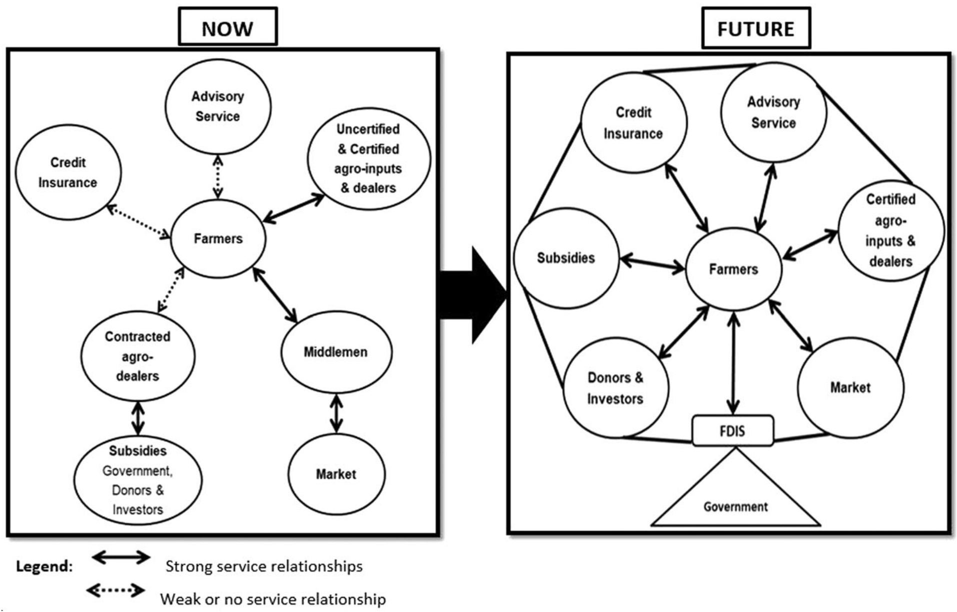

Figure 1. A conceptual model for sustainable agriculture in Tanzania.

services and, in some cases, their absence and the target for a future comprehensive digital solution for smallholder farmers in Tanzania.

3. Research method

We followed the design science research (DSR) method in this study. According to Hevner et al. (2004), the DSR method is used to design digital artifacts solutions that interact with the problem context and facilitate the development of an effective and efficient information system. We customized the DSR method process by Peffers et al. (2007) from six to eight steps: problem identification, requirements, preliminary artifact design, user survey, refined artifact design, implementation, evaluation, and communication. According to the DSR method, problem identification comes first so that subsequent processes can focus on the development of the artifact solution. The problem identification can emerge from the existing literature (problem-oriented initiation), the users' needs (context/user initiation), or from a desire to achieve a particular objective (objective-centered solution) (Peffers et al., 2007; Siemon, 2022). The second step is collecting the requirements or defining the objectives necessary for solving the identified problem. A third step is about designing preliminary artifact based on the requirements of the previous step. The fourth step is conducting a user survey which involves orienting potential users with solution design and understanding user context related to the problem, thereby getting useful feedback to improve the initial design leading to a participatory design (Hartson & Pyla, 2019). Since this study is a problem-oriented initiation, we added a 'user survey' step between artifact design and implementation to get the stakeholders' feedback (user or context initiation) for possible improvements of the original artifact design for an effective and efficient information system. The fifth step is to refine the artifact design based on the identified stakeholders needs and opinions. The sixth step is pilot implementation, which involves presentation and demonstration of a part or all of the artifact solution to potential users. This step is crucial for artifacts development; designers and developers can leverage user feedback to improve the design through process iteration. The seventh step is an evaluation by

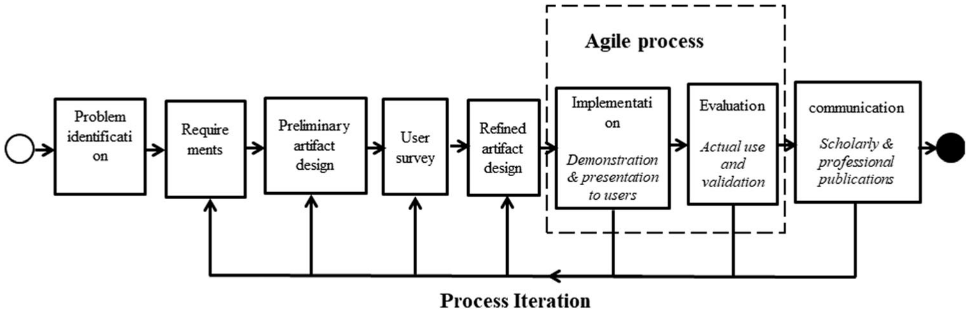

Figure 2. A DSR method used in this study, inspired by Peffers et al. (2007).

implementing an artifact solution to a problem, and consists of monitoring the effectiveness and efficiency of the system; thus, feedback can be used to iterate back to the system design. The eighth step is communication, documenting the system through scholarly and professional publications (Peffers et al., 2007). Figure 2 highlights the instantiation of the DSR for our research, with the seventh step revisiting all previous steps to allow for an empirical refinement approach in the design of the artifact solution (Hevner et al., 2004).

Heeks (2016) argued that IT development can be seen as socio-technical systems where IT and society interact by shaping each other. In addition to the survey (fourth step) that gives stakeholders (society) a chance to participate in the design of the artifact, the agile methodology allows the stakeholders to intervene in the redesigning of the system during its development. The agile methodology starts from the planning to the development phases with short spans of iterative and incremental interactions of stakeholders over the process and tools throughout the project's lifecycle (Al-Saqqa et al., 2020). This practice allows changes to be made during development without jeopardizing the process or having to restart from scratch.

We first identified the problem of smallholder farmers through a systematic review of scholarly articles and gray literature (Mushi et al., 2022), followed by the conceptual design and actual artifact design. We conducted two forms of literature searches: in Web of Science (WoS), IEEE Xplore, and in related databases (FAO, Google Scholar, and Research4Life) to identify existing digital technologies used in the agriculture sector globally. Except for the Tanzanian agriculture sector, to obtain a detailed technological context, we limited the search to six years, from 2015 to 2021, to find the most recent development in digital technologies. We then evaluated their availability to smallholder farmers and sustainability in the agricultural context. We searched local repositories (Sokoine University of Agriculture), WoS, and Google Scholar to identify common challenges for smallholder farmers and selected and analyzed recent publications of digital artifacts solutions developed to solve smallholder farmers' challenges.

Requirements for the preliminary design of the FDIS artifact emerge from this existing literature. The artifact takes smallholders' challenges as requirements and develops the means necessary to mitigate the challenges toward sustainable services for smallholder farmers, including common services such as advisory services, markets, subsidies, quality farm input, and financial services. We mapped these requirements into three groups: (1) resources and ICT sustainability, (2) economic requirements and (3) environmental sustainability requirements.

4. Results – artifact design and description

The FDIS data management system for smallholder farmers' services consists of stakeholders who play different roles in a complete farming cycle. Based on the conceptual model presented in Figure 2, the FDIS platform will comprise five modules: (1) farmers' data, (2) agro-dealers data, (3) farm input data, (4) advisory and (5) market services (see full description in sub-sections below).

The platform is purely driven by data from farmers and involves stakeholders such as agro-dealers and financial institutions. Therefore, after setting up the digital infrastructure, the first activity is to collect data that different actors can access and provide different services to farmers. We propose that the FDIS be managed by the government or by a public-private partnership because of the important role the government can play in networking the agricultural sector by combining various services under one roof (Rao, 2004; United States Department of Agriculture, 2002). Therefore, government-led implementation of the system should result in more sustainable agriculture – economic sustainability, environmental sustainability, and sustainability of the ICTs infrastructure and resources (Mushi et al., 2022).

4.1 Farmers' data module

The FDIS data management system for smallholder farmers should consist of comprehensive data for government, donors, investors, and other stakeholders enabled services. Like farmer profiling (Boyera & Grewal, 2020; Gray et al., 2018), the platform should include personal data that uniquely identifies a farmer, including the national identification number. Personal information should consist of elements essential to the services, such as literacy level, income, language, level of control of the farm, and details of farmer communication to find out their preferred channel of information dissemination, mainly regarding advisory services. Location information of the farmer is also critical for subsidies, tailored insurance, and credit services. Important location details include an administrative address from regional or township, district, ward, division, village, street to plot number, and Global Positioning System (GPS) coordinates. An Application Programming Interfaces (APIs) could be used to connect and verify individual farmers' identities in the national schemes of personal identification, such as the National Identification Authority (NIDA) in Tanzania. Blockchain technology is also essential to immutably record uniform and portable personal data (Gray et al., 2018). Therefore, farmers could share their data with stakeholders they wish, such as financial institutions for a service.

In addition, stakeholders need farm information to determine actual needs and provide specific support to farmers. Farm details include GPS coordinates, crop type, farm registration details, farm labor, and equipment for farming activities. According to Boyera and Grewal (2020), sometimes farmers manage several fields in different places or one piece of land divided into sections for different crops. In this case, land information such as location, size, ownership, crop and soil information is useful to support smallholder farmers. Linked to a field, production information that includes planting details, pests, and diseases with their treatments helps prepare post-harvest activities.

Most farms in Africa are uninsured; only approximately 650,000 farmers have access to insurance out of more than 40 million smallholder farmers in sub-Saharan Africa alone (Hazell & Hess, 2017), which is less than 2%. Nonetheless, financial instrument information available to farmers, including credit, subsidies, insurance, mobile money, and bank accounts, is vital for financial services. Credit information enables smallholder farmers to access credit services in line with financial instruments. Credit information includes credit history, farm production plans, and membership in micro-finance institutions. Moreover, insurance information allows other stakeholders to understand the scope of coverage, the level of production risks covered, the type of insurance company, the recurring costs, and the amount payable to farmers if the insured risk occurs. The platform offers the opportunity to improve or adopt index-based farm insurance, which scientists and organizations consider particularly effective (Hazell & Hess, 2017). These digital artifacts could potentially influence investments in insurance companies that support smallholder farmers in times of crisis.

Agricultural knowledge and farmer training, mainly through farmers' cooperatives, will enable smallholders to participate in modern farming by learning best practices in investment and management of production resources, thereby increasing production and income. Therefore, information on the qualification of the farmers constitutes an essential dataset that has implications for the value of the farm products, which is critical to marketing. Certification and training must be registered at different levels, such as farm preparations, planting, pesticide and herbicide use, irrigation, and other farm management activities, including harvesting. In addition to the marketing segment, business information, namely agribusiness linkages, cooperative membership, market-related to the farmer, quantity harvested and sold (at the farm, cooperatives), and price sold, plays a significant role in connecting farmers to the market (Gray et al., 2018). Data about farmers should be as complete as possible to allow quality and tailored services such as subsidies distribution, advisory services, credit, and insurance (Prause et al., 2021). Here we present the conceptual solution to the farmers' problems identified in the literature (Table 1). These identified problems are not the only ones that the information system will address, and we are in the process of conducting a user survey that may highlight additional needs, based on which we will refine the design of the artifact. This survey should also allow us to assess the validity of our model's hypotheses, which are based on case studies (presented in Section 5). Therefore, a concrete design of the FDIS will address the issue identified in Table 1 and other issues that may arise from stakeholder opinions. Table 1 summarizes the essential dataset categories and problem solutions for smallholder farmer services in a complete farming cycle.

4.2 Agro-dealers' data module

Agro-dealers play an essential role in the distribution of farm inputs and enable smallholder farmers to adopt new technologies in agriculture throughout the country. However, a study by Rutsaert et al. (2021) on the geographical distribution of agro-dealers in Tanzania shows that most smallholder farmers in rural areas use very few modern farm inputs due to the lack of agro-dealers services. The few agro-dealers in remote regions face high demand and less competition, allowing them to charge higher prices to smallholders and have fewer product choices in stock (Rutsaert et al., 2021). Furthermore, some agro-dealers and their products are not certified by the authorities, resulting in the distribution of substandard inputs (Kahwili, 2020), which results in low production, poor quality products, and a negative impact on the environment and consumer health. Most smallholder farmers in Tanzania do not use industrial fertilizers (Elliot, 2016); thus, they depend on organic manure and natural land nutrients, decreasing soil fertility and crop production in the short term. As a result, smallholder farmers engage in deforestation to find new arable land, which has a negative impact on the environment and contributes to global climate change.

Agro-dealers' data module will enable policymakers, government authorities, and investors to better understand the distribution networks of agro-dealers across the country and improve the current situation toward sustainable agriculture among smallholders. By analyzing farmer data and the distribution of agro-dealers, investors can identify opportunities, especially in remote areas, allowing farmers to have a wide choice of stoked farm inputs products at a fair price. Smallholder farmers will also be able to identify certified agro-dealers and farm inputs to combat substandard inputs from uncertified dealers. Agro-dealers' data should include business name, administrative address, registration details, location with GPS coordinates, certification, and a list of services such as delivery and advisory services to farmers.

4.3 Farm inputs data

Domestically produced or imported agricultural inputs must undergo quality controls and verification before being distributed. Like many African countries after independence, the importation and distribution of farm inputs were centrally controlled by state organizations in Tanzania. Until the 1970s, the government had the Tanzania Seed Company for seeds and the state monopoly of fertilizer distribution at a subsidized price under the 1967 Arusha Declaration. However, the state then faced a debt crisis, delays, and shortages in input distribution and allowed the private sector to enter the market (Elliot, 2016). Many private sectors are involved in importing and distributing farm inputs registered and certified by government authorities. Despite the involvement of the private sector, only about 15% of the seeds planted are registered and approved by the responsible authorities, and about 2,500

Table 1. Farmers data and services for sustainable agriculture.

Problem description	Data categories (Boyera & Grewal, 2020; Gray et al., 2018)	Data type (Boyera & Grewal, 2020; Gray et al., 2018)	Issues to address
Poor decision, cheating and fraud in selecting and distributing subsidies to smallholder farmers (Masinjila & Lewis, 2018)	Personal information	Full names, identity numbers, gender, family details (marital status, size, family leader gender), land size and ownership status, income level, education level, other source of income	• Transparency in selecting and allocating subsidies • Increase trust of other stakeholders e.g. financial institutions
Existing advisory and extension services are too general for farmers to comprehend and practice	Communication Information	Language preferences, preferred channel of communication, phone details (number, smart/ basic phone, phone literacy), preferred type of information (market, crop)	• Tailored advisory and extension services • Right information to right farmers through a right channel
Distance between farmers and service providers e.g. input traders is a challenge (Rutsaert et al., 2021)	Location details	Current and permanent physical addresses: regional/district/ ward/division/plot and GPS coordinates	• Inputs delivery services and new agro-dealers investments in demand areas • Useful data by other stakeholders
Inability of services providers to assess farmers' production risks and opportunities	Farm data Field data	Farm registration, employee/labor, farm tools, crop type(s)/variety Field location, soil, size, land title, GPS coordinates, and crop history	• Tailored advisory services such as inputs, credit and market services • Insurance services covering risks linked to field location and crop type
Poor access to financial (credit and insurance) services (Kimaro, 2020; Sanka & Nkilijiwa, 2021; Simbakalia, 2012)	Financial instrument	Mobile money and bank accounts; accessed credit, insurance and subsidies	• Provide payable loans and financial advisory services
	Credit Information	Credit history, business plan, cooperative societies membership, active credit (loan size and use)	• Help farmers to create good farm business plans
	Insurance data	Insured field, insurance cost, risks covered, insurance company, amount repaid if the risk(s) occurs	• Identify uncovered risks • Useful for credit services (de-risking loans)
Agricultural knowledge of smallholder farmers is unknown; thus, it is difficult to determine their service packages	Qualification and certification data	Training and certification dates in different levels and stages of farming, Training/certification institutions Certificates of adhering to farming standards	• Access unique market such as organic food products • Advisory service based on the knowledge gap • Identify needs and provide training in anticipation • Increase quality of products and environment
Smallholder farmers do not record production information, making it difficult to prepare post-harvest activities	Production data	Planting data (amount of seeds, date, spacing, tools used, intercropping) Input data (irrigation, herbicides, fertilizer, pesticides) Pest and diseases attacks, rainfall, yield, loss and storage	• Yield prediction and post-harvest activities preparations e.g. storage and market • Real-time advisory and information services to farmers • Early warning services

(*Continued*)

Table 1. Continued.

Problem description	Data categories (Boyera & Grewal, 2020; Gray et al., 2018)	Data type (Boyera & Grewal, 2020; Gray et al., 2018)	Issues to address
Poor access to market and middlemen market disruption (Misaki et al., 2016; Navuri, 2018)	Business information	Agribusiness linkages, market expected by the farmer, price, total product sold (at farm, market, cooperate), cooperative membership	• Predict different market that farmers can use • Enable farmer to connect with the market and ensure transparency of transactions

Source: Author's compilation.

tons of agrochemicals were registered in Tanzania in the mid-2000s (Elliot, 2016). Studies suggest that informal farm inputs smuggled across neighboring countries dominate the market.

Moreover, most of the pesticides and seeds in Tanzania are forged in different ways, such as reprinting product labels, diluting chemicals, and copying package shapes. For these reasons, Tanzania has had a low yield per hectare compared to other developing countries. For example, the average yield of maize is 1.5 tons per hectare, while the World Bank estimates 6–7 tons when farmers use adequate and quality inputs (World Bank, 2012).

Publishing and sharing data of the registered and certified farm inputs would solve the problem of substandard farm inputs distribution. Essential data about farm input include the manufacture details, international registration details, importing or supplying agent information, registration and certification data by Tanzania authorities, usage data, and unique verification code. Therefore, farmers will be able to identify the registered agents or suppliers and verify the originality of the farm inputs such as seeds, fertilizers, and agrochemicals. The effort also requires a campaign to sensitize farmers to use quality farm inputs and their benefits.

4.4 Advisory service module

The lack of comprehensive advisory service is the cause of the low adaptation of modern farming techniques by most smallholder farmers (Jack & Tobias, 2017). The Tanzania government employs outreach officers to disseminate information and advice farmers on modern farming, including farm inputs, to solve the problem. The Tanzania Agriculture and Livestock policy, revised in 2000, defines the outreach service as a transfer of agricultural technology from experts to farmers, livestock keepers, and other stakeholders (United Republic of Tanzania, 1997). However, outreach officers are limited by the number of farmers they can visit; thus, most smallholder farmers rely on traditional farming knowledge from other farmers and family members. In addition to the farmers' advisory information system developed and implemented by Sanga et al. (2013), the FDIS can provide more tailored advice from experts based on farmers' data such as location, type of soil, crop, farm equipment, and more. Agricultural Research Institutions (ARIs), through information and outreach services sections such as the Sokoine National Agricultural Library (SNAL), provide outreach information services to farmers across the country (Mushi & Egbukole, 2021). Therefore, ARIs could use farmers' digital information systems to repackage information based on the needs, literacy level, crop or livestock, and other farmers' attributes for effective advisory and outreach services to smallholder farmers (see Figure 3).

4.5 Market service module

The farm product market is the core of agribusiness success and economic sustainability. The FDIS for farmers will provide market data such as different markets and product prices. This information is essential for smallholder farmers to find the right market for their products and thus earn a deserved income. Furthermore, the platform will allow farmers to publish their yield information and meet directly with potential buyers without the intervention of intermediaries in the value chain (Figure 3). Thus, farmers will have many market options through cooperatives, trade channels, and on-farm sales fed by market price information.

5. Illustration with four Tanzanian case studies

The general research question regarding the feasibility and impact of FDIS at the farmer level cannot be answered directly. This is akin to modeling complex ICT for development problems, in which a theoretical framework must be supported by case studies that provide a context in which that theory will be reconciled (Samoilenko & Osei-Bryson, 2021). For this reason, we focus on lower-level research questions supported by our theoretical model represented by the identification of four common challenge cases in Tanzania that illustrate how the design of the FDIS interacts with and solves farmers' problems in distributing subsidies, accessing financial services, avoiding low-quality farm inputs, and accessing the market without involving intermediates in the value chain. To ensure adoption and validation of the service by the various stakeholders it is important to correctly understand their needs. To this end, we are conducting interviews with different FDIS stakeholders (farmers and livestock keepers, agro-dealers, insurances companies, financial institutions, ministry of agriculture, government subsidy office, and customers). On the basis of the gathered information, we will then refine our artifact design and later implement FDIS, regularly validating our model with the stakeholders as depicted by the feedback loops in Figure 2.

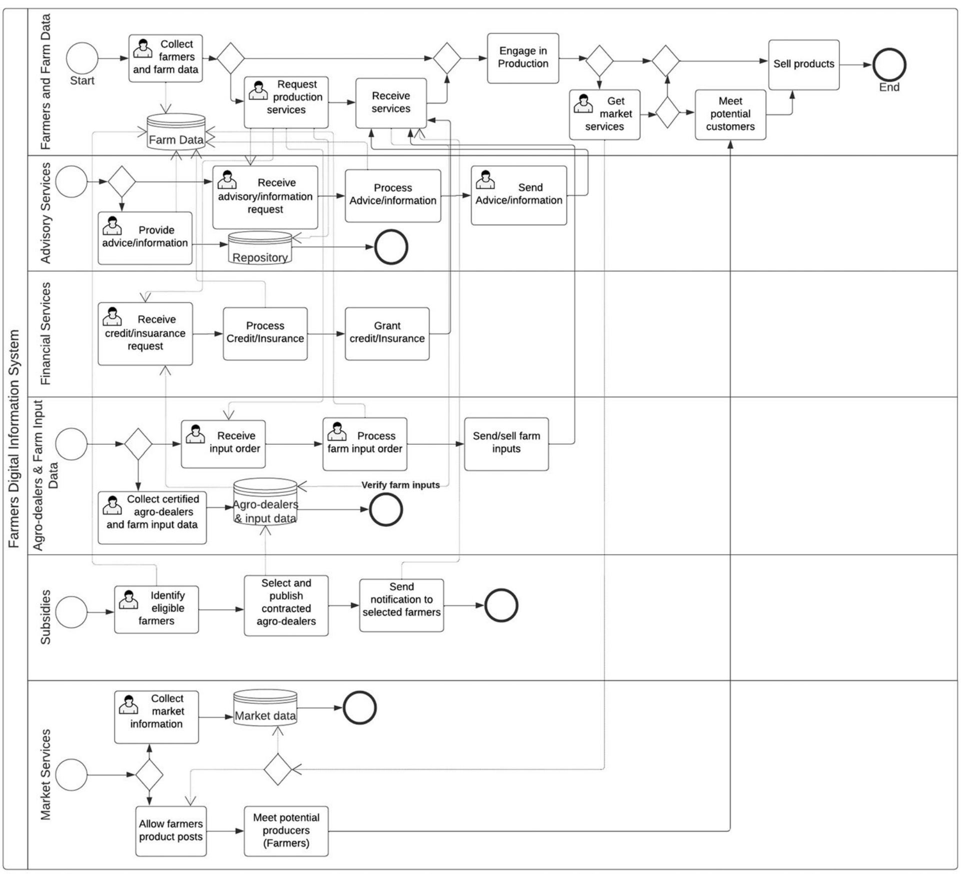

Figure 3. FDIS and farmers access to services BPMN diagram.

5.1 Case 1: subsidies

The Tanzania government has supported smallholder farmers through subsidies since independence. From the 1960s to the early 1970s, the government monopolized the agro-inputs market and controlled importation and distribution at a subsidized cost to enable smallholder farmers to increase production and income. Later, in the mid-1970s, the government faced a colossal debt crisis, delays in input delivery, and a shortage of these products, which allowed the private sector to enter the market (Elliot, 2016). Nevertheless, the government maintained the subsidies programs for smallholder farmers through contracts with private suppliers. Since its independence, Tanzania has had 16 National Agriculture Input Voucher Systems (NAIVS) contracts between government and input suppliers (Masinjila & Lewis, 2018). The agreements require suppliers to sell inputs such as seeds, fertilizers, and agrochemicals at a half-market price to selected smallholder farmers. The study on the effectiveness of the NAIVS suggests that the programs had a low impact on smallholder farmers due to cheating and fraud (Masinjila & Lewis, 2018). The subsidies did not reach the targeted farmers because of biases in the selection process, contracted agro-dealers denying to be part of the program and therefore selling inputs at a full-market price to subsidized farmers. For this reason, the majority of smallholder farmers do not use quality farm inputs, resulting in low production and income.

The FDIS data management system for smallholder farmers has the potential to solve the fraud and cheating in the distribution of subsidies. Data about farmers and agro-dealers is essential for transparency in selecting smallholder farmers and access to farm inputs from contracted suppliers at a half market price or any other agreement conditions. Suppose the subsidy coordination office uses the FDIS to select smallholder farmers. Then it will be possible to allocate subsidies to them based on specific criteria and send them notifications with a list of contracted agro-dealers from whom they can purchase subsidized farm inputs. The FDIS could provide data on selection criteria such as women-headed families, low-income families, farm size, and land ownership to facilitate the selection of appropriate smallholders. At the same time, farmers will be able to directly identify contracted suppliers. As a result, the targeted smallholders will be more likely to adopt the new technologies, thereby increasing their productivity and income (see Figure 3). The system could ultimately improve the impact of NAIVS programs in Tanzania and reduce extreme poverty and food insecurity among a growing population.

5.2 Case 2: Substandard farm inputs

After the liberalization of the input market, the government formed agencies for different input quality verification and registration for local and imported farm inputs, such as, the Tanzania Fertilizer Regulatory Authority (TFRA) for fertilizers, the Ministry of Agriculture, Food Security and Cooperatives – seed unit (MAFSC-Seed Unit), the Tanzania Official Seed Certification Institute (TOSCI) for seeds, the Tropical Pesticides Research Institute (TPRI), and the Tanzania Atomic Energy Commission (TAEC) for agrochemicals verification and registration (Elliot, 2016). These agencies aim to guarantee the quality of inputs for increased production and preservation of the environment. The quality of farm inputs is among the factors contributing to increased production and income so that farmers can get a return on their investment. However, studies show that 85% of seeds planted in Tanzania are not registered, and the input market, mainly agrochemicals, is dominated by products smuggled from neighboring countries (Elliot, 2016). Regular operations by government authorities in agro-dealers stores uncover substandard inputs that contribute to low production and high risks to human health and the environment. For instance, 'less than a quarter of agro-dealers are checked each year, and the amount of counterfeit seed circulating in the market is estimated to account for at least 25–35% of all commercial seed' (Elliot, 2016, p. 13).

On the FDIS platforms, data on inputs registered and verified by regulatory authorities will be published to allow farmers to access inputs from the registered agro-dealers. Imagine a farmer using the FDIS on a smartphone, tablet or computer to search for verified quality of farm inputs: they will be able to find the nearby registered agro-dealers and verify the inputs through a FDIS platform, as shown in Figure 3. The platform could include a digital verification for incoming products, such as a barcode or quick response code for easy verification. Such a practice will also enable the automatic removal of unregistered products and agro-dealers from the market.

5.3 Case 3: Financial services

Smallholder farmers have limited access to credit and insurance services (Sanka & Nkilijiwa, 2021), which hinders the uptake of quality farm inputs and modern farm equipment to increase production. However, agricultural financing has a potential role in sustainable agriculture among smallholder farmers globally. Tanzania has experienced low agriculture production in the long term despite its abundant arable land and favorable climatic condition. Many studies link low production to lack of access to credit services; most poor farmers cannot adopt new technologies and farm inputs to increase production (Elliot, 2016). The majority of smallholder farmers, especially in rural areas, depend on cooperative institutions as a source of credit. Cooperative institutions are formed locally and loans are only granted to known members of the association who provide micro-savings as collateral for the loan (Sanka & Nkilijiwa, 2021). However, loans from cooperative institutions are limited based on members' micro-saving, limiting the farmers' ability to invest in agriculture. A study on access to credit in Tanzania shows that only 1% of total bank lending goes to the agriculture sector. The banking industry in Tanzania anticipates high risks of lending to smallholder farmers (Simbakalia, 2012). Most farms are uninsured due to farmers' financial illiteracy, low willingness to pay, and lack of trust in insurance providers (Osumba et al., 2020).

A data management system for smallholder farmers is essential for access to financial services in Tanzania. Credit services could enable farmers to adopt modern farm equipment and quality inputs for increased production and income. Farmers' data can be shared with financial institutions through APIs. For instance, a farmer using the FDIS platform could apply for a financial service, the financial institution could ask the farmer to share his/her information for evaluation purpose. Comprehensive data on farmers, farms, production, insurance, credit history, and business information can reduce the banking industry's risks in lending to farmers. The information would enable financial institutions to analyze the highest loan amount for a farmer, the ability to pay, and recovery measures if they fail to pay the loan. Likewise, insurance companies can use a similar method to offer insurance services for smallholder farmers. Index-based agriculture insurance, which seems promising for smallholder farmers (Hazell & Hess, 2017), requires farmers and field data to analyze potential risks of farmers that need to be insured. Access to credit and insurance will increase smallholder farmers' confidence, and investment in agriculture hence fostering economic development, increased production, and increased employment, especially for most unemployed youth in urban areas, reducing poverty and food insecurity.

5.4 Case 4: Market access

Market access has been a critical challenge to most smallholder farmers in developing countries, including Tanzania. Lack of market information is the bottleneck of the smallholder farmers toward participating in agribusiness. Middlemen take advantage of farmers' lack of market information by buying at a low price, usually on the farm, and selling the product at a high cost to the consumers (Oguoma et al., 2011). It is heart-breaking: a report from Tanzania mentions that many farmers aim to produce mainly for (low) consumption because of regular losses in the market when they want high production for their business (Navuri, 2018). Most smallholder farmers practice subsistence agriculture; they avoid taking risks for higher production that could help increase their income, solve the country's malnutrition problems, and make the agriculture sector more dynamic.

The use of the Internet and Information Technology (IIT) has a significant impact on selecting productive sales and marketing channels, increasing farmers' income (Zhang et al., 2021). The market module of the FDIS framework will provide updated information on different markets and product prices. This information is vital to farmers when bargaining to sell their products to aggregators, consumers, agro-food processors, and other stakeholders in the market value chain. A farmer with an FDIS platform on his/her smartphone, computer, tablet, or other device could access the market price of all products (the farmer can use information to decide on future crops to plant, livestock, or post-harvest planning), use the virtual market for farm products by directly meeting potential buyers at a reasonable price (thus eliminating intermediaries in the market value chain), resulting in an incentive for increased production and income for smallholder farmers.

6. Discussion

The FDIS platform has the potential to reduce risk for farmers and stakeholders involved in agriculture – promising increased productivity and income, reducing inequality by empowering women in agribusiness, stimulating economic development, and solving the world's pressing challenge of producing enough nutritious food for a rapidly growing population. The digitization of the national agriculture system has the potential to empower the majority of smallholder farmers through the services provided by stakeholders in a full farming cycle. We propose a public or public-private managed digital system for the potential role of government in mobilizing the stakeholders and resources needed to empower smallholder farmers for sustainable agriculture.

6.1 An FDIS toward sustainable agriculture

Smallholder farmers could achieve sustainability in the agriculture context – economic sustainability, environmental sustainability, ICTs infrastructure, and resources sustainability, as smallholder farmers have access to financial (credit and insurance) and tailored advisory services that would enable them to invest in modern farming techniques, improved farm equipment, and quality inputs, resulting in increased production (Mushi et al., 2022). Furthermore, an FDIS could increase profitability by facilitating access to market information and linking smallholder farmers with potential customers. Therefore, an FDIS can help smallholder farmers to achieve economic sustainability – increased production and income. An FDIS can play a role in environmental sustainability through ecological conservation and reducing the impact of ICT on the environment. The ability of smallholders to identify certified and registered farm inputs, particularly agrochemicals and fertilizer, could eventually lead to the elimination of counterfeit products that could harm the ecology and health of consumers. Moreover, increased uptake of quality inputs such as fertilizers at a required amount would make the cultivated area productive for the long term, avoiding deforestation in seeking new arable land. FAO report that cultivated area will increase by 12% in developing countries, particularly in Sub-Saharan Africa and Latin America, while decreasing by eight percent (8%) in developed countries by 2050 (FAO, 2009).

It should be noted that the FDIS platforms also contribute to environmental pollution mainly through carbon emissions in data centers. Therefore, to reduce the environmental impact of ICT, portable devices (for data collection and service access) such as smartphones and tablets are encouraged, as they are energy efficient (Jindal et al., 2012). We propose using the green fog computing model to implement the FDIS architecture to diminish carbon emissions and high energy consumption in centralized data centers (Qureshi et al., 2021). In the hierarchal arrangement of fog nodes, small data centers in each region will act as a fog with the ability to use renewable energy sources such as wind and solar power, thus less carbon emissions and energy consumption, which is promising for environmental sustainability. FDIS platforms use ICT infrastructures, which require financial and human resources to manage in order to provide long-term digital services to smallholder farmers. Those infrastructures require regular maintenance, hardware and software upgrades, and qualified staff to ensure the daily operation of the system. In addition, collecting and updating data requires human intervention to ensure data quality. An FDIS as a public or public-private managed platform will operate under public office, thus, receiving financial and human resources from the government. To fund the FDIS, the government can generate revenue by charging stakeholders such as financial institutions, agro-dealers, and the market to support ICTs infrastructure and resources sustainability. An FDIS as a public-managed platform would be more services-oriented than a profit-based business model. Therefore, the fee should be as low as possible, which should not affect the income of smallholder farmers.

6.2 Toward an implementation of an FDIS

6.2.1 Infrastructure and resources for FDIS sustainability

Several factors surround ICT projects to ensure their successful implementation and sustainable operation. While a critical enabler, investment in ICT infrastructure alone cannot produce the desired socio-economic impact (Bollou & Ngwenyama, 2010). Therefore, complementary investments such as good policy, an education system, stable electricity service, a skilled workforce, and other resources are essential for the sustainability and maximum impact of ICT projects (Ngwenyama & Morawczynski, 2010).

The proposed FDIS is an ICT project that aims to have a socio-economic impact at the national level by enabling smallholder farmers to access essential services that maximize their production and income. The envisaged system requires investment in ICT infrastructures such as communication networks, data centers, Internet services, ICT devices and other related tools, which drive the impact (Samoilenko & Osei-Bryson, 2021). Samoilenko and Osei-Bryson (2021) added that these drivers attract activities, investments, and resources such as a skilled workforce, electric service, and sound policy for successful and sustainable operations for the desired socio-economic implications. Current investment in ICT infrastructure, particularly wireless communication (Sinda, 2021), rural electrification (Bensch et al., 2019), and rural farmers increasing mobile usage and Internet access (Msoffe & Lwoga, 2019) in Tanzania are promising drivers for the implementation and sustainable operation of the FDIS framework. In addition, the national education system fosters the availability of a skilled workforce such as ICT specialists, data management experts, logistics personnel, and many other human resources needed to make a maximum socio-economic impact for the country. ICT in support of the country's agriculture development policy is also critical to the planned implementation of the FDIS, stakeholder adoption and sustainability of the platform. For instance, an ICT policy to digitize the national agricultural system could rally all stakeholders, identify new areas of skill development, logistics, and food supply chain development, and other events necessary to achieve the desired economic outcome.

FDIS as a disembodied digital artifact solution – which runs on computers, smartphones, tablets and similar devices and is not tied to specific livestock, crops, or farm equipment (Birner et al., 2021), would require access to public data such as spatial and non-spatial agricultural information to function. Although lagging behind, some governments in low- and middle income countries are beginning to provide public data to support the agriculture sector. For instance, the 'AGIS Comprehensive Atlas' in South Africa provides a wide range of spatial data services, including land use, soil quality, crops and vegetation, climate change, national agricultural infrastructure, and others (Open Data South Africa, 2022). Public data plays an important role in agriculture, including supporting farm advisory services, planning, crop management, post-harvest activities, investments, pest and disease control, and agriculture research, to name a few.

6.2.2 Leveraging available infrastructure and resources

There are some existing services that we can adapt to the FDIS platform without developing them from scratch. A study should be conducted to identify the current services to be included in an FDIS. For instance, electronic data on registered and certified farm inputs published by responsible government authorities (Elliot, 2016) and advisory information systems (Sanga et al., 2013), as well as mobile applications such as the one to combat substandard farm inputs (Shao & Edward, 2014). However, most existing services may require modifications to achieve the desired benefits to smallholder farmers. An FDIS would also need data exchange mechanisms such as linking to a national identification system to collect farmers' identities and exchanging data via APIs with services providers, primarily financial institutions. Data collection for FIDS is an expensive task and requires substantial financial resources during project implementation because it involves a large number of staff and equipment. Nevertheless, outreach workers across the country in Tanzania could be responsible for regularly updating data from their regions after the project's duration. Therefore, an FDIS could use minimal resources by effectively utilizing existing government human and material resources.

6.3 Issues related to data

FDIS is a data-driven artifact solution for smallholder farmers. Therefore, the implementation of the solution requires prior consideration of various data-related issues. These issues include data protection, data quality, data ownership and sovereignty.

6.3.1 Legal issues on data protection

FDIS collects, stores, and shares personal data with third parties for services to smallholder farmers. Tanzania is currently drafting its personal data protection legislation (UNCTAD, 2021), which will strongly regulate data collection, storage, and sharing of such information. Until then, FDIS will require implementing a specific process aligned with the legislation. The common principle of 'purpose limitation' can be applied to protect both personal and non-personal data, that data should not be used for any other purpose than those consented by the farmers and other stakeholders (FAO, 2021). Although requirements among countries vary, the common legislation for collecting, storing, and sharing personal information requires the farmers' consent. It lets them know the purpose and the list of organizations with which the information will be shared (Boyera & Grewal, 2020). Therefore, the implementation of an FDIS will require a training and awareness campaign for smallholder farmers on the purpose and benefits of collecting, storing, and sharing their data with other stakeholders. Farmers will also need to sign consent forms to allow the sharing of information with stakeholders providing the necessary services in a complete farming cycle.

6.3.2 Data ownership and sovereignty

Data sovereignty is a rich and multi-dimensional concept, but it is usually tied in some way to control of the data life-cycle, i.e. collection, storage, access, use and reuse, including deletion (Hummel et al., 2021). Data sovereignty also raises concerns about government authority over data hosted in foreign clouds, as it depends on the laws of the country in which the data is located (Irion, 2012). Moreover, the introduction of data management model solutions in agriculture poses new data sovereignty challenges, as agricultural technology providers can take control of the data collected (Prause et al., 2021). Consequently, the question arises who owns the data between the farmers, the companies, or the organizations that manage the digital platform? The simple answer is that farmers own the data, sometimes mentioned in the contracts; however, this may not be addressed in them (FAO, 2021). The complexity of data ownership and legislation is due to its non-tangible nature compared to other objects. FAO (2021) mentions that legally, data is not exhaustible: it can be copied, transferred, and migrated, and the same data can be in different locations and owned by different people. As an ad hoc solution, the FDIS platform could adopt existing legal and regulatory frameworks dealing with data ownership (Townsend et al., 2019), as future legislation could resolve some issues around data ownership. Similar to a digital farmer profiling platform (Boyera et al., 2017; Gray et al., 2018), an FDIS collects data that can be 'captured' – leveraging the data collected from the users of the platform for commercial purposes, potentially selling the data to investors, advertisers, product or service innovators (Fraser, 2019). Schrijver (2016) mentioned that giving farmers control over their data flow to other stakeholders builds trust with farmers for data exchange and benefits services for sustainable agriculture. Therefore, farmers and stakeholders should have ownership and control rights, such as deciding on the sharing of data for other purposes and its reuse to prevent agricultural technology providers from taking it. Indeed, farmers should control and decide on the data generated by their actions to benefit all partners involved and not fall victim to a 'data grab' that only benefits agricultural technology providers (Fraser, 2019; Prause et al., 2021). For instance, through an open data charter that would enable the design of open repositories for farm data, farmers could share some or all of their data, such as the sharing of data from a particular farm or crop with a partner to facilitate planting, chemical or fertilizer application, post-harvest services, etc. (Puri, 2016; Fraser, 2019; Prause et al., 2021). In addition, an FDIS requires a legal and regulatory framework that grants 'data owners' the right to delete their data and opt out of the platform completely, thereby ensuring ownership and protection of farmers' data, which, without stricter rules, is currently being allowed to be taken over by agricultural technology providers (Prause et al., 2021). Increased public and private sector investment in ICT infrastructure in Tanzania (Sinda, 2021) could attract domestic hosting of the FDIS framework to achieve data sovereignty. However, foreign clouds could also be helpful with a high encryption mechanism to protect data from unauthorized access and use (Winandy, 2011).

6.3.3 Data quality

Data quality is essential for the FDIS to effectively and efficiently provide services to the farmers and stakeholders involved in a complete farming cycle. In this regard, data quality refers to the completeness, timeliness, accuracy, consistency, and precision of the data. The FDIS will collect and capture static (i.e. personal information) and dynamic data that require regular updates, such as crop status and production information. FDIS could use APIs to connect and verify farmer identities in national personal identification systems to ensure consistency in individual farmer data. As an incentive, it is essential to train farmers and other stakeholders on the importance of updating their data and the quality issues, not just that of provider services. Autonomous data collection, such as sensors and unmanned ground and air vehicles (UGV and AV), could ensure data quality; however, these tools require a huge upfront investment (Daum et al., 2021). In general, the manual tasks of data collection and update could involve well-trained staff, including extension agents, in collaboration with farmers and other stakeholders. Indeed, as part of the data quality control process, FDIS will apply verification and validation procedures to ensure data validity and reliability.

6.4 FDIS and smallholder farmers' empowerment

Smallholder farmers will mainly access the FDIS platform through mobile phones. The increased penetration of inexpensive mobile phones (prices consistently decreasing) and access to Internet in rural areas (Silver & Johnson, 2018), create opportunities for empowering smallholder farmers globally. A recent report on the digitization of African agriculture indicates that around 33 million smallholders were using digital apps in 2019. This number is expected to grow to about 200 million smallholders by 2030 (Technical Centre for Agriculture and Rural Cooperation (CTA) 2019). Ayim et al. (2022) ascertained that text and voice-based services over mobile phones are the main ICTs adopted by smallholder farmers in Africa to improve access to accurate and timely agricultural information. Similarly, a study in Tanzania shows that mobile phones are essential tools for rural farmers in accessing information and communication, leading to various development outcomes (Msoffe & Lwoga, 2019). Therefore, integrating these services into the FDIS platform will allow farmers to access personalized information and advisory services from experts and outreach officers on-farm preparation, sowing, and recommended farm inputs for soil fertility, crop protection, and increased agricultural productivity. Also, an FDIS provides timely dissemination and access to early warning information to prevent severe crop losses; examples include weather advisories and related risks such as drought and floods, crop diseases, and pest outbreaks. An FDIS could enable timely communication of research output and agriculture technologies from Agriculture and Research Institutions (ARIs), including the Tanzania Agricultural Research Institute (TARI), which has a network of 17 centers, and universities. The ARI's main tasks involve disseminating produced knowledge to the agrarian community across the country for farmers to adopt modern farming. ARIs, in collaboration with media (community radio) and outreach officers, can become reliable sources of information and advisory services for farmers, raising awareness and building agribusiness skills. Unlike farmers who rely on traditional sources of information such as word-of-mouth from fellow farmers, community elders, family members, and superstitious beliefs (Misaki et al., 2016). An FDIS allows ARIs, experts, and outreach officers to repackage and disseminate information based on farmers' literacy level, perceived information needs, location, types of crops or livestock, and other information. These tailored information and advisory services could significantly improve modern farming practices for sustainable agriculture among smallholder farmers. Generally, farmers will be able to make informed decisions on various farming activities in a complete farming cycle.

An FDIS connects smallholder farmers with a network of service providers, namely financial institutions, agro-dealers, agronomists, donors, investors, and business and government services over various matters that empowers farmers. For instance, some donors and investors commit to empowering different levels (poor, moderately poor, and abysmal) of smallholder farmers, as in USAID's 'Feed the Future' program in Tanzania (USAID, 2021). An FDIS could provide information to identify these groups and the positive impacts on targeted smallholder farmers. Policymakers will also access vital information to understand different smallholder farmers' concerns better, thus designing and implementing policies that benefit smallholder farmers and promote agriculture and rural development.

6.5 IT and human development

An FDIS is an IT-based framework solution for smallholder farmers aiming to foster economic growth in developing countries. According to Heeks (2016), digital development is a socio-technical system in which ICTs and society are interconnected and influence each another. The process involves social-technical systems that include socio-economic and political aspects that participate in the design, use and management of digital development (Heeks, 2016). The design, use and governance of the FDIS framework adhere to the principle of IT for development as it involves national-level agriculture stakeholders and digital technology for socio-economic development. An FDIS involves stakeholders from the initial stage of artifact design (user survey) through implementation and evaluation that entail the use and governance of digital development.

An FDIS has the potential to enable smallholder farmers access to financial services for investment in agriculture, achieve increased agricultural products and find reliable markets which results to increased income and social well-being of the society. The digital framework also strengthens the country's agricultural value chains as it brings together critical agricultural stakeholders, namely farmers, agro-dealers, processing industries, consumers, government, donors and investors. An FDIS promotes transparency, collaboration and inclusiveness of the marginalized groups such as rural farmers, women and indigenous communities. Policy and decision makers can access reliable information about different matters of smallholder farmers and design policies that stimulates economic development of the country.

6.6 Challenges of implementing FDIS framework

Although it looks promising, the FDIS framework may face various challenges that could hinder its full potential. First and foremost, digital literacy is vital for all stakeholders involved in the farming cycle. Despite the spread of smartphones and Internet penetration (Schroeder et al., 2021), digital literacy remains a barrier to digital solutions in developing countries (Lopez & Aminu, 2021). It can affect the adoption and use of the FDIS framework, data quality (manual entry), and the overall services provided by service providers. In addition, the digital divide between literate and illiterate people, large and small farms, women and men, and industrialized and developing countries may emerge (Birner et al., 2021). Digital literacy training for farmers and stakeholders is critical to the performance of the FDIS framework. The challenge of incentives to extension workers, farmers, agro-dealers, and other stakeholders could affect manual data entry, thereby distorting the quality of services. Therefore, raising awareness and encouraging all stakeholders to manually enter data could ensure quality of data and services to all relevant stakeholders (Daum et al., 2021). Agricultural policy directly influences the adoption of ICT as impact driver (Samoilenko & Osei-Bryson, 2021). Creating policies that encourage the digitization of the national agriculture system could lead to successful implementation of the FDIS framework. Like other digital agricultural data management solutions, FDIS may face the challenge of policy frameworks and guidelines that address data ownership, sovereignty, privacy, and security issues due to the unique nature of the data (Daum et al., 2021; FAO, 2021). The integration of different data from different sources and formats could be a setback for the FDIS framework; however, the problem can technically be addressed during implementation. In addition, limited access to public data in most developing countries (Birner et al., 2021), could affect the quality of services under FDIS frameworks. The government should consider making public data (i.e. spatial and non-spatial agricultural information) accessible for sustainable agriculture via the envisioned framework.

7. Conclusion

7.1 Digital artifact summary

We presented FDIS, a vital digital artifact for sustainable agriculture, especially for governments directly involved in decision making, regulation, and control of different aspects that affect the agriculture sector. FDIS could provide effective and transparent means for government involvement in the agricultural sector through accurate and timely information. In most developing countries, governments have considerable influence over the agricultural sector, which affects the market and distribution of inputs, stakeholder investments, and the market of agriculture products. For instance, through its agencies, the Tanzania government is involved in the importation and registration of farm inputs, subsidies programs, agriculture financing, and controls export markets of agriculture products. The government could oversee the distribution of quality farm input throughout the country and the prices of these inputs, which are high in some areas due to the cost of transportation, resulting in low adoption by farmers (Elliot, 2016). Therefore, in collaboration with input suppliers, the government could implement mitigation strategies to reduce the cost of inputs in the identified areas in order to increase the use of quality inputs and increase the productivity and income of smallholder farmers.

The FDIS operation could prompt the government to review existing flawed policies and reforms (Cooksey, 2012) to promote growth in the agriculture sector. Moreover, stakeholders and farmers could prepare local and international markets through early production estimations. Also, it is easy to identify, control and communicate early warnings about disasters and other potential risks such as pests and diseases (Cooksey, 2012). Indeed, the FDIS platforms encourage transparency in government services and control such as subsidies distribution, combating substandard inputs, and regulating input and farm products market prices.

An FDIS is an opportunity to grow and develop private sector investment in agriculture. It could eliminate unfair competition between registered and certified farm inputs and uncertified ones produced locally or smuggled from neighboring countries. The platform provides essential data for investors, such as agro-dealers services in areas with high input demand and processing industries in regions with sufficient raw materials. These improvements could attract most unemployed youth who have left agriculture and moved to urban areas in search of better income-generating jobs. An

FDIS promotes sustainable agriculture, a more active role for government and other stakeholders, and whose practical implementation can eliminate existing challenges and make agriculture a reliable sector for youth employment and food production. It further stimulates IT for human development through increased income and profitability, inclusion of underrepresented people such as rural farmers, women and other marginalized groups. Thus, it contributes to achieving zero hunger and reducing extreme poverty – the first and second Sustainable Development Goals of the United Nations.

7.2 Future work

This study proposes a comprehensive digital platform for sustainable agriculture among smallholder farmers. To contextualize the general model, we illustrate it from four case studies in Tanzania. We believe that a platform that pulls together key stakeholders would solve common challenges of smallholder farmers by enabling access to essential services in a complete farming cycle under one roof through a single point of entry. The next step will be to interview these stakeholders, whose responses will allow us to strengthen our model according to the loops illustrated in Figure 2. The article stimulates similar research on developing digital solutions that brings together critical stakeholders for the economic, political and social development of people. The presented Business Process Modelling and Notation (BPMN) diagram (Figure 3) for different FDIS modules is the first concrete step toward developing our platform. To the best of our knowledge, this is the first artifact that focuses on a comprehensive solution to common challenges and transparency of services toward sustainable agriculture among smallholder farmers. Practitioners can play a significant role of mobilizing resources and stakeholders to achieve this digital development in agriculture sector. In future work, we plan to demonstrate part of the artifact solution and conduct a user survey in Tanzania to assess the applicability of this FDIS artifact by stakeholders for the implementation of the sustainable agriculture platform. The survey could identify missing service components and data sets for smallholder farmers and other stakeholders. This testing of our model against the harsh realities of smallholder farmers could prompt a redesign to improve the artifact.

Notes

1. Most studies mention economic and partly environmental sustainability as the two components of sustainable agriculture. In addition, Mushi et al. (2022) consider other resources, ICTs infrastructure sustainability and green computing (environment sustainability) essential components of sustainable agriculture.
2. Although FDIS is designed for Tanzania's national agricultural system, it can be adopted in the context of any other developing country.

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Appendix C

Article III: State of Agricultural E-Government Services to Farmers in Tanzania: Toward the Participatory Design of a Farmers' Digital Information System (FDIS).

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Article

State of Agricultural E-Government Services to Farmers in Tanzania: Toward the Participatory Design of a Farmers Digital Information System (FDIS)

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Abstract: The projected population increase and drastic climate changes are a great setback to food security through sustainable agriculture. However, governments need to play key roles in supporting the agriculture sector, which creates considerable employment and contributions to most countries' Gross Domestic Product (GDP) outcomes. In many countries, the governments already support the agriculture sector with services based on Information and Communication Technology (ICT) to reach many stakeholders, including smallholder farmers. This paper investigated the status of e-Government services in the agriculture sector for farmers in order to understand the functions and scope of e-services, the challenges faced by farmers, both addressed and unaddressed, and the challenges of ICT-based services for farmers and other stakeholders in Tanzania. We used a qualitative research approach to interview the Ministry of Agriculture, farmers, extension workers, and agriculture processing industries. The main finding reveals that e-government services play a major role in the agriculture sector in Tanzania. Our results show that the pre-existing ICT services identified for farmers cannot meet the needs of farmers in a complete farming cycle. Moreover, lack of awareness, digital illiteracy, and poor infrastructure are the major challenges faced by farmers and other stakeholders when it comes to ICT-based services. These results justify the need for a comprehensive digital platform, particularly the proposed Farmers Digital Information System (FDIS) to enable farmers and other stakeholders to access essential services in a complete farming cycle for a more sustainable agriculture.

Keywords: agriculture; e-Government services; ICT services; sustainable agriculture; Farmers Digital Information System (FDIS); Tanzania

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1. Introduction

Food insecurity and extreme poverty are among the major challenges of low- and mid-income countries, including Sub-Saharan Africa. The major threat to food insecurity on the continent include climate change and projected population growth, with Sub-Saharan Africa leading the way with a growth rate of 114% in 2050 [1]. Moreover, the global political crisis, such as the war between Russia and Ukraine, has led to food shortages, particularly in African countries [2]. The digitization of agriculture services is essential to enable farmers to adopt climate-resilient practices for the development of the agrifood system [3]. Governments, particularly in low- and mid-income countries, can play a major role in supporting the agriculture sector, which makes a significant contribution to countries' GDP and provides employment for more than half of the population [4]. According to the Organization for Economic Co-operation and Development (OECD) [5], Information and Communication Technologies (ICTs) can help governments to improve services to citizens in a cost-effective, transparent, accountable, and highly convenient way through e-Governments.

e-Government is a concept that emerged from the impact of ICTs on development, and which has led to the reform of public administration. e-Government has many different definitions based on the purpose and context of use. For instance, the OECD [5] defines e-Government as the use of Internet and ICT as tools for better governance, while the United Nations [6] refers to the phrase "digital government" as the use of ICT to communicate information and services to citizens and businesses. The United Republic of Tanzania [7] defines it as:

> "The use of ICT to enhance work efficiency and improve service delivery in order to meet the needs of the public in a responsive and transparent manner. e-Government is expected to facilitate the interaction between the Government and its clients including the citizens (G2C) and business communities (G2B), as well as within the public administration itself (G2G)".

Generally, we can define e-Government as the use of ICT to deliver services and interact not only with its citizens, but all stakeholders involved in government and business activities in a transparent, accountable, and timely manner. Indeed, developed and developing countries alike have adopted an e-Government strategy, which plays a major role in delivering information and services to citizens in a more comprehensible environment [8,9]. The agriculture sector, in particular, has witnessed a number of e-Government initiatives designed to help farmers and other stakeholders increase production. A few examples include the Online Fertilizer Recommendation System (OFRS) in Bangladesh, which generates location-specific fertilizer recommendations to help farmers use inputs efficiently, thereby reducing input costs and safeguarding the environment and consumers' health [10]; e-Government in India, which provides services in general agriculture activities, i.e., farming, livestock keeping, and fishing [11]; China's digitization of agricultural and food supply chains, which focuses on empowering the majority of rural farmers [12]; and agricultural mobile applications that support different crops and livestock management, developed by the Kenya Agricultural and Livestock Research Organization (KALRO) [13].

The Tanzanian government has supported the agriculture sector since its independence by developing optimal policies, maintaining subsidy programs for farmers and finding markets for agricultural products. As part of the implementation of the e-Government strategy [7], the Ministry of Agriculture (MoA) introduced e-services, taking advantage of the increased use of mobile technologies and the Internet to reach a wide range of stakeholders, particularly farmers. While there is evidence of some digital government services in the agriculture sector, there is less literature on existing active services for stakeholders, particularly for the majority of smallholder farmers in rural Tanzania.

This paper is part of a wider study to design and implement a state-owned (or public–private) Farmers Digital Information System (FDIS) so that farmers can access all essential services under one roof. We conducted a comprehensive literature review of advances and experiences in digital technology in developed and developing countries, including Sub-Saharan Africa and Tanzania in particular [14]. The literature review identified the challenges facing smallholder farmers in Tanzania, and the knowledge gaps that could be addressed through digital technology. We used the problems identified by farmers to develop the preliminary design of the FDIS for sustainable agriculture among smallholder farmers [15]. In addition, we planned to study e-Government services in agriculture and the opinions of farmers and other stakeholders in Tanzania for the future design of a concrete FDIS. Therefore, this paper aims to investigate e-Government services in agriculture for farmers in order to understand the functions and scope of e-services, the challenges of farmers that have been addressed and those that have not, and the challenges of ICT-based services for farmers and other stakeholders in Tanzania. The results of this study are essential to the future participatory design of the Farmer Digital Information System

(FDIS)—a proposed government digital platform that provides services to farmers as part of a complete farming cycle.

2. Methods

Using a qualitative research approach and cross-sectional design, we interviewed the Ministry of Agriculture (MoA), 22 crop farmers, 4 processing industries as customers for agricultural products, and 9 extension workers (qualified agricultural personnel responsible for training and technology transfer from research centers to farmers, with a view to increasing agricultural production [16]) in different regions in Tanzania. We focused on the crop farmers, as there are no e-Government services for livestock farmers. We considered the regions producing the main cereal crops, with the selection of farmers and extension workers evenly distributed across regions. Data collection took place from December 2022 to April 2023. The study aimed to identify active digital services provided by the government to the farmers, and the strength and challenges of ICT-based services. The approach was useful in gathering all stakeholders' opinions on the identified themes. We used purposive sampling to select participants from the MoA because of their central and unique roles in providing services to agriculture stakeholders in the country.

The study areas (regions, district, and wards) were selected based on the criteria of higher production among the three major cereal crops, which were maize, wheat, and paddy (see Figure 1). Extension workers were purposely selected because they were the only source of information on the performance of digital services for farmers at ward and village levels. We used a simple random technique to select farmers in the identified wards as all farmers at this level possessed common characteristics. The study targeted access to digital services by smallholder farmers in rural and semi-urban areas. Indeed, we collected essential data to understand the status of e-Government agricultural services to empower farmers and the challenges of all stakeholders involved. Figure 1 below shows the sites visited as part of this study.

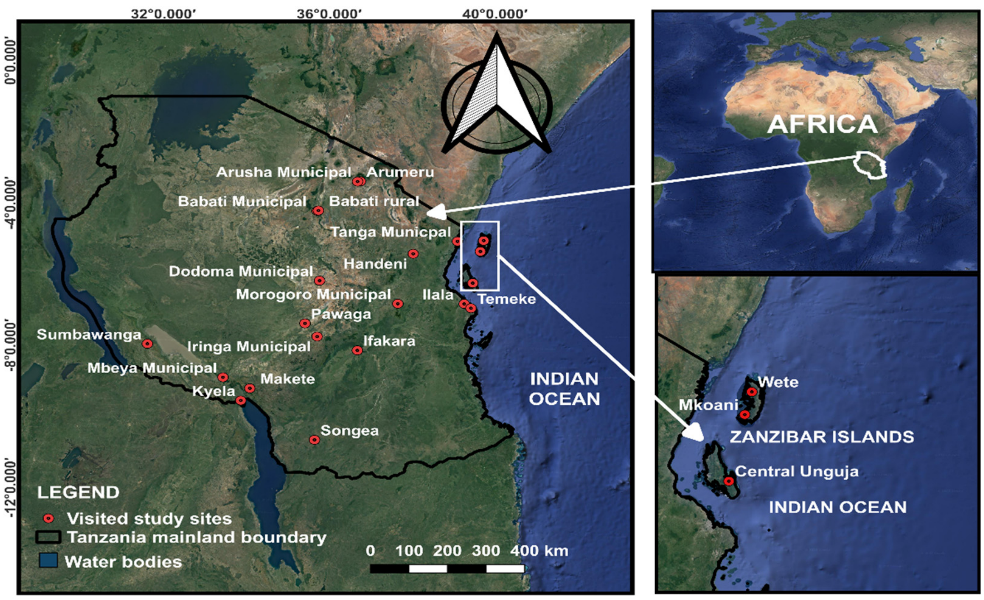

Figure 1. Map of Tanzania showing study districts and sample distributions.

3. Results

We adopted a thematic analysis approach and used the ICT-based services offered by the MoA to farmers as themes for presenting the results of the study. The findings show three active ICT-based services to farmers offered by the Tanzanian government through the MoA. The themes include a Mobile Kilimo (M-Kilimo) application with a web-based extension services, a call center, and the Digital Fertilizer Subsidy Distribution System (DFSDS). All three services are managed in the extension services section of the

MoA. Our study examined the findings on platform operation, stakeholder awareness, usage, and challenges related to farmers' access to digital services. Table 1 below shows the demographic characteristics of the cereal crop farmers that took part in this study.

Table 1. Demographic data of crop farmers (n = 22).

Variable	Category	Frequency (n)	(%)
Location (Regions)	Mbeya	4	18
	Rukwa	4	18
	Iringa	3	14
	Tanga	3	14
	Morogoro	2	9
	Manyara	2	9
	Ruvuma	2	9
	Mjini Magharibi	2	9
Location status (ward level)	Rural	15	68
	Semi-urban	7	32
	Urban	0	0
Gender	Male	14	64
	Female	8	36
Age group (years)	21–30	3	14
	31–40	3	14
	41–50	10	45
	51–60	4	18
	61 and older	2	9
Educational level	No formal education	0	0
	Primary education	17	76
	Secondary education	4	18
	Diploma	1	6
Farming activity (occupation)	Maize farming	9	41
	Rice (paddy) farming	8	36
	Wheat farming	5	23
Farm size	Below 3 hectares	1	5
	4–6 hectares	14	64
	7–9 hectares	7	31

Source: field data [17].

3.1. M-Kilimo Application

M-Kilimo is a mobile application and a web-based extension service freely accessible to farmers for consultations on various issues related to agriculture (crop farming, livestock keeping, and fishing). The service was launched in May 2020 and is available on the Android operating system, via Unstructured Supplementary Service Data (USSD) and on a website (http://exts.kilimo.go.tz/) (accessed on 12 December 2023). The MoA mentioned that the aim of M-Kilimo was to reach many farmers across the country with extension services. The services that farmers and other stakeholders can access on this platform include price information, the sale and purchase of agriculture products, and advisory services.

Extension service refers to knowledge and technology transfer from experts to farmers for the development of agriculture. Anaeto et al. [18] argued that effective agricultural extension services are critical to the development of the agriculture sector in any nation. For this reason, the Tanzania government has taken various steps to strengthen the agriculture extension system by recruiting grassroots extension workers at the national level, building the capacity of extension workers, and developing appropriate methods for delivering extension services [16]. However, the number of extension workers recruited is low in relation to the needs of Tanzania's farmers. To overcome this lack of extension workers, M-Kilimo is the digital approach that enables extension services to be provided to most farmers, including in areas where there are no extension workers.

Farmers can register through a USSD code, the website, or by downloading the M-Kilimo application. The findings show that most farmers used the USSD to register and use the M-Kilimo application. Farmers are encouraged to register themselves, but the system transmits the data to an extension worker in the relevant ward or district, who checks the farmers' data to ensure data quality. Extension workers are registered on the USSD and then work through the website. Potential buyers must also register for the service to meet farmers and facilitate the agribusiness. Farmers and other stakeholders can access the following services through M-Kilimo:

1. To access the prices of agriculture products: the farmer selects the price and the type of crop to receive a summary of the different markets and price information.
2. To sell: the farmers select this option to indicate the amount they want to sell (in kilograms, sacks, or tons) and the price. This information is made available to the public, and potential buyers can consult it and contact the farmer to achieve their business goal.
3. To buy: the farmers can select the agriculture products they wish to buy and receive a list of sellers with full details, such as contact and crop information.
4. Advisory service: stakeholders (farmers or buyers) can submit their requests by selecting the type of agriculture activity (crop farming, livestock keeping, or fishing), then write and submit a request. The system forwards the request to the sender's ward or district extension worker for a response. Requests that have not been answered at the ward level for a certain period of time are automatically transferred to the sender's district and regional level, and to the MoA for a response. Extension workers at all levels can also direct the requests to experts for answers.

M-Kilimo features a feedback option, enabling stakeholders to send comments on the provided services or opinions on other agriculture-related issues. Table 2 below shows the data on the M-Kilimo extension services offered to farmers by the MoA.

Table 2. M-Kilimo application service.

Name of the Platform	When Launched	Registered Stakeholders		Usage Statistics	
M-Kilimo application	May 2020	Farmers	7,269,106		
		Extension workers and experts	9985	Number of consultations (advisory services)	75,623
		Customers	24,523		
		Agricultural products sellers	26,927	Replied queries	73,839

Source: field data [17].

This study identified the challenges posed by the M-Kilimo digital extension services proposed to the various stakeholders, in particular the extension workers, buyers, and farmers. The findings reveal that the extension workers play significant roles in the M-Kilimo application. Extension workers are people trained in agriculture and employed by the government to provide training and transfer technology from research centers to farmers in order to increase agricultural production and productivity [16]. Extension workers also play a key role in farmers' adoption of digital services, as they help promote the M-Kilimo application to farmers and other stakeholders, help farmers register, approve farmers' data for registration, train farmers to use the services, and answer farmers' inquiries. However, many extension workers have not been properly trained or provided with the tools they need to deliver their services. The extension workers could only access the M-Kilimo application via the Internet, using advanced digital devices such as smartphones, tablets, and computers, but they were not provided these devices as working tools. On the other hand, no incentives were provided to extension workers to perform the job, despite using their own devices and money to purchase Internet bandwidth. Generally speaking, the results show that extension workers make little or no use of the M-Kilimo application to provide services, due to various limitations.

Moreover, the MoA mentioned farmers' digital illiteracy as an obstacle to using the M-Kilimo application. According to the MoA, the majority of farmers use the USSD method for self-registration, which is challenging to most farmers. The slow typing speed observed during farmers' self-registrations in USSD leads to incomplete data and inquiries due to the system time-out. The study ascertained that there were approximately 400,000 incomplete registrations out of around 7.2 million registered farmers. USSD has a word limit per Short Message (SMS), but some farmers and extension workers exceeded the word limit when expressing or answering questions, leading to incomplete services. Furthermore, the MoA reported that telecommunication services were limited in some rural areas, to the extent that it was impossible to connect to at least the USSD network during the farmer registration outreach program. All farmers and processing industries interviewed in this study were not aware of the M-Kilimo application and extension services provided by the MoA.

The MoA acknowledged that the provision of services through the M-Kilimo application had suffered significant setbacks, particularly in terms of the support provided by extension workers. However, the government plans to acquire and distribute digital devices to all extension workers in the country. It also plans to establish partnerships with telecommunication companies so that extension workers can access the Internet free of charge.

3.2. A Call Center

The Tanzanian government through the MoA launched a call center service in July 2022 to enable wider access of extension services to the majority of farmers. This was performed to achieve a better inclusion of farmers who could not access the M-Kilimo application for various reasons, such as digital illiteracy or poor Internet services in rural areas. Farmers are free to call the center with any questions they may have about the agriculture sector and receive rapid answers or a callback. All stakeholders can ask anything about the agriculture sector, whether they relate to crops, livestock, fishing, marketing, or agro-inputs, to name but a few.

The call center is open 15 h a day (07:30–22:00 h), 7 days a week, with staff qualified in general agriculture. Moreover, queries that cannot be answered instantly by the staff are submitted to experts for professional consultations, then communicated to the sender through a callback service (see calls stats in Table 3). The service is only accessible in Tanzania through a public mobile number. The findings reveal that the method used for awareness campaigns are broadcast media (radio and television) and the website. The MoA has indicated that digital extension services through the M-Kilimo application and a call center aim to fill the gap of the required extension workers. The government has employed around 6704 extension workers out of the 20,538 needed, which represents only 32%, meaning that the majority of farmers have no access to extension services. The established and future digital services to farmers can fill the gap by reaching more farmers who have access to mobile phones and other digital devices. Table 3 below shows data of the call center extension service offered to farmers by the MoA.

Table 3. A call center extension service.

Name of the Platform	When Launched	Registered Stakeholders	Usage Statistics	
A call center	(July 2022)	All agricultural stakeholders are encouraged to call for suggestions, complains, request information, or seek professional advice	Total calls	5202
			Callbacks	2301

Source: field data statistics [17].

The study investigated the challenges posed by digital extension services via a call center. The findings reveal that low stakeholder awareness of the proposed service is a barrier to access, particularly for the majority of farmers living in rural areas. This is due to a weak campaign to promote the service in the short-term mass media and on websites. An MoA officer argued that "many rural farmers are not aware of the call center yet, but we are planning to promote the service through live media coverage in radio and televisions, and social media" (MoA, Dodoma).

3.3. Digital Fertilizer Subsidy Distribution System (DFSDS)

Since independence, the Tanzanian government has maintained its subsidy program, particularly for fertilizers for farmers. Until recently, subsidy distribution was performed manually through the local government from the ministry level to regional, district, ward, and village administrations. This distribution process faced many challenges, including corruption, cheating, and fraud, which resulted in poor access to subsidies by many smallholder farmers. Large- and medium-scale farmers used corrupt leaders to access large amounts of the subsidies and deny access to most smallholder farmers. On the other hand, agro-input traders used the opportunity to illegally export subsidized inputs to neighboring countries [19]. Therefore, this method of distribution was ineffective and had little impact on the farming community.

The government has realized the potential of digitizing the subsidy distribution service to eliminate or minimize the challenges of the old distribution method. In September 2022, the government launched the DFSDS to manage the distribution of fertilizer to all farmers in Tanzania. The DFSDS is managed by a government agent, the Tanzania Fertilizer Regulatory Authority (TFRA), and services are housed in the extension services section of the MoA. The findings reveal that, despite some challenges, the farmers who are registered receive the subsidies as expected. The findings also show that many farmers receive fertilizer subsidies for the first time under the new digital distribution system. This justifies the claims about the vulnerability of the manual distribution method and the effectiveness of the digital distribution approach. The DFSDS registers the main stakeholders in the fertilizer supply chain, which include importers, manufactures, agro-dealers, and farmers. Table 4 below presents statistical data from the DFSDS.

Table 4. Fertilizer distribution statistics.

Name of the Platform	When Launched	Registered Stakeholders		Usage Statistics
Digital Fertilizer Subsidy Distribution System (DFSDS)	September 2022	Farmers	2,828,300	Over 350,000 farmers received subsidies by 16 January 2023
		Importers	29	
		Manufacturers	3	
		Agro-dealers	3181	

Source: field data statistics [17].

Farmers are registered at village and ward levels by extension workers in collaboration with the local government administration. The study findings show that some telecommunication companies were used to speed-up the registration process, but the government stopped their participation due to poor-quality data for the registered farmers. Important registration information includes personal details, such as national identity and mobile number, location, and size of the farm. Once a farmer is registered, the system generates a unique number and sends it to a farmers' mobile number through a Short Message (SMS). A farmer can use the unique number and identity card to claim subsidized fertilizer from the nearby contracted and registered agro-dealer. Farmers are allocated a number of subsidized fertilizer bags based on the size of their farm, as indicated during the registration process. The system also sends an SMS to the farmer for each bag of fertilizer sold, with its unique number, to prevent the use of other peoples' contact details to claim the subsidy (see Figure 2).

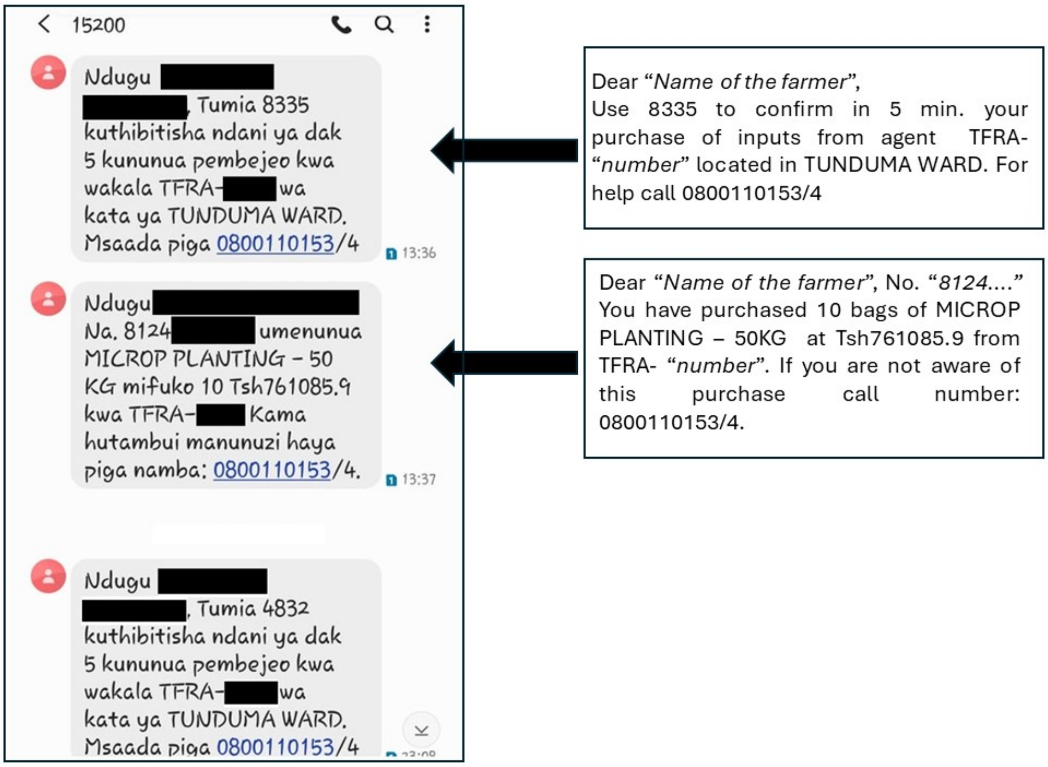

Figure 2. An example of an SMS sent to a farmer via the DFSDS.

The government selects and registers the importers and manufacturers involved in the subsidy program. Normally, the agreement with importers and manufacturers is to distribute and sell fertilizer to all farmers in the country at a half market price, with the government compensating for the other half. Importers and manufacturers select and work with agro-dealers in all regions in the country. The agro-dealers sell at a half price and record the transactions of the sales to all subsidized farmers with their unique numbers. This information is submitted to the importers and manufactures, then to the government for reimbursement. In this case, the government only compensates for fertilizers to which farmers have access, which improves accountability and transparency in the supply chain.

The main challenge identified for the DFSDS is the low quality of data from registered farmers. This can be due to farmers' lack of awareness of the service's objectives, and intentional cheating by farmers and extension workers. For instance, some farmers reduced their farm size during registration due to the fear of tax impositions on their land. This automatically affected the number of subsidized fertilizer bags assigned to their unique number. Some farmers exaggerated the size of their farm in order to be allocated numerous bags of subsidized fertilizer, which they could claim at half the market price and sell at a higher price on the black market. This fraud provides access to subsidized fertilizer for illegal export to neighboring countries. For instance, 400 bags of subsidized fertilizer were seized in the Songwe region, while being transported to Malawi [20]. A lack of resources has contributed to this situation of poor data quality, as an extension worker looks after an average of 2000 households, making it difficult to verify each farmer's holdings. Thus, the registration process was slow, and many farmers were not registered for the subsidy program. To speed up the registration, the government allowed some telecommunication companies and banks to register farmers through their branches in the country. However, the government immediately halted the approach due to incorrect data entries during farmers' registrations.

4. Discussion

4.1. General Observations

The Tanzanian government has played a major role in the development of the agriculture sector since its independence. The digital services introduced are part of the e-Government project aimed at serving the growing population and meeting service demands with limited resources [7]. The main strength of the government is to adopt ICT for development and encourage the digitalization of services in various sectors. However, ICT-related projects face various challenges in low- and middle-income countries, including Tanzania. The major setback to e-Government agricultural services for farmers in Tanzania is the approach to implementing digital services, the digital divide, and financial and other barriers [8]. Existing digital services were implemented using a top-down approach; key stakeholders, including users, were therefore not involved in the initial design phases. The approach is cited as one of the main factors in the failure of ICT-based projects in developing countries, including Africa [21]. The top-down approach to implementation is characterized by decision making and control; thus, stakeholders are not involved in the early stages of service design, and the key factors and environmental conditions for successful implementation are inadequately taken into account [22]. This study also revealed that the M-Kilimo application and the DFSDS were for the first time introduced to extension workers and farmers for actual use. It involved a short training course for a few regional representatives of extension workers, in the form of a Training of Trainers (ToTs) to train other extension workers in their respective regions. Next, the extension workers had to train farmers and register them on the digital platform so that they could use it. Indeed, users of digital services are not equipped and motivated to adopt and use the system, as the results indicate.

This study was purposely carried out in rural and semi-urban areas where agriculture is the main economic activity for the majority of small-scale farmers. Therefore, apart from constant power outages in all regions in Tanzania, some areas, such as Ngana (Kyela district), Lumemo (Ifakara district), and Mollo (Sumbawanga district), have not been electrified, affecting access to technology. In addition, it was observed that digital illiteracy and inadequate ICT infrastructure, particularly in rural areas, were major obstacles to farmers' and extension workers' access to technology. For instance, poor network coverage was observed in Mkata ward (Handeni district), Lumemo ward (Ifakara district), Galapo ward (Babati district), Ngana ward (Kyela district), Mollo ward (Sumbawanga district), and some villages in the Matogoro ward (Songea district).

Moreover, the existing agricultural e-Government services do not meet the farmers' needs in a complete farming cycle. Farmer's unmet needs, as identified by Mushi et al. [14], include access to farm-specific advisory services, farm management information, credit, and insurance services. Duplicating efforts in existing digital services wastes time and resources. This is due to the absence of digital innovation plans that build on and leverage existing systems and services. For instance, the M-Kilimo application, established in 2020, registered more than 7.2 million farmers while the DFSDS launched in 2022 started registering farmers from scratch. This duplication of effort would not have happened if an integrated data-sharing system had been in place. Figure 3 shows existing non-integrated e-Government services for farmers in Tanzania.

Although the e-Government services offered to farmers help solve a variety of problems, such as extension services to farmers in remote areas, and reducing fraud and cheating in the distribution of government fertilizer subsidies, these services do not solve the critical problems of a complete farming cycle, such as access to specific farm advisory, credit, and insurance services. Figure 3 shows the duplication of existing digital services, in particular, farmer registrations for the M-Kilimo application and the DFSDS. Moreover, these services operate independently leading to low-quality services and inconveniences. For instance, call center experts and consultants have no access to farmer data in any of the existing systems for specific farm advisory services. What is more, a farmer registered in the M-Kilimo application will also have to register on the DFSDS, and so on for future systems.

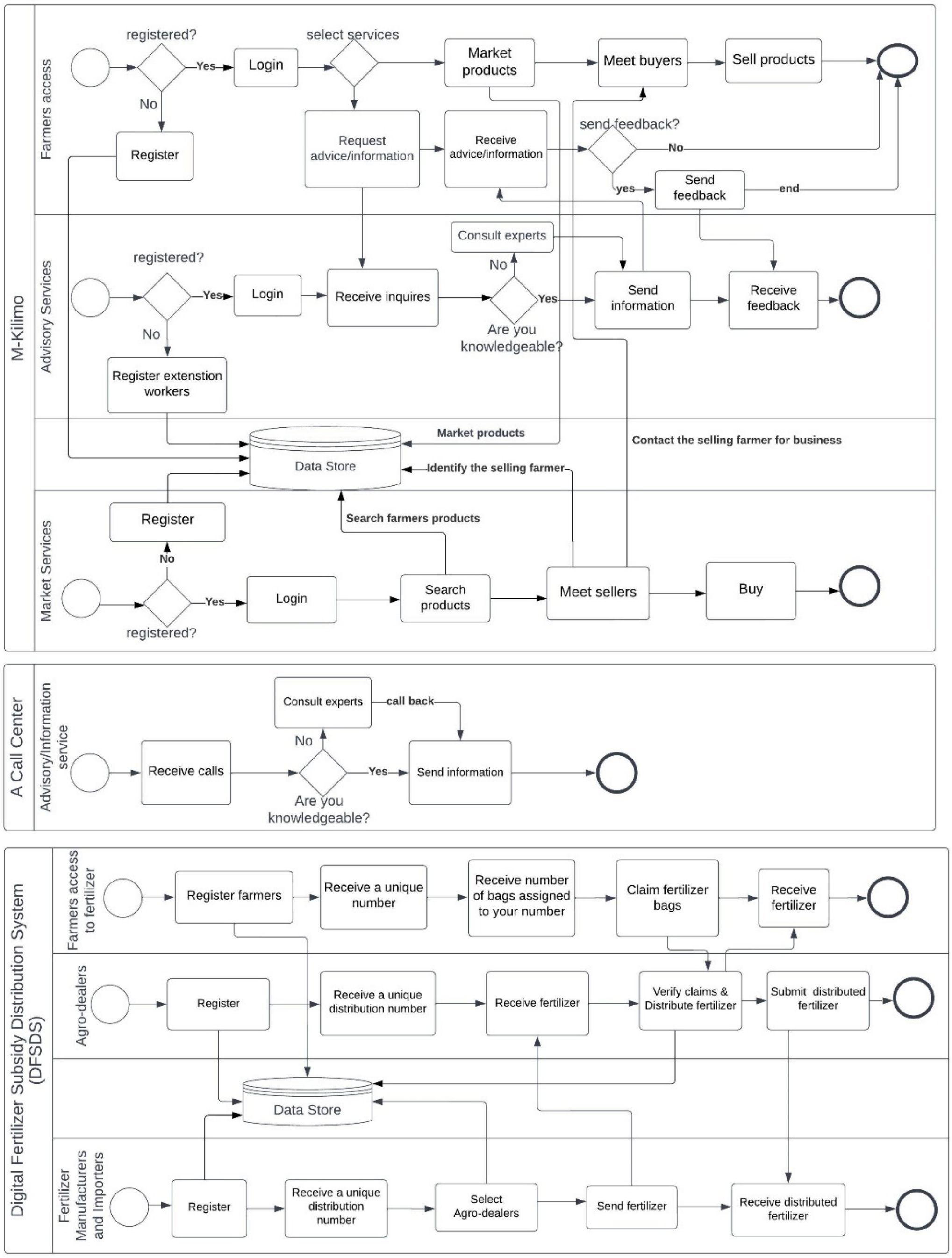

Figure 3. Existing non-integrated e-Government services for farmers, represented in the form of a Business Process Model and Notation (BPMN).

The use of USSD codes was the predominant method of smallholder farmers' access to the M-Kilimo and DFSDS services. This is because most smallholder farmers have basic mobile phones and few own smartphones. A study by Silver and Johnson [23] found that Tanzania was the Sub-Saharan country with the lowest rate of mobile device ownership by adults, whereby 62% of adults owned basic mobile devices, 13% owned smartphones, and 25% had no phone at all. Therefore, the use of USSD codes was seen as an effective method for enabling the majority of smallholder farmers to access e-Government agricultural services. Moreover, USSD codes operates well, even in limited network-coverage situations, making it effective for most farmers in rural areas [24,25]. The major obstacle to the use of USSD codes revealed by this study is the digital illiteracy of many farmers in rural and semi-urban areas. Otherwise, USSD code services remain an effective method of reaching the majority of people living in remote areas with limited ICT infrastructure.

The study also revealed that many farmers and other stakeholders were unaware of the digital services offered by the government. Indeed, the M-Kilimo and DFSDS services, which involve farmer registration, have not registered even half of Tanzania's estimated 20 million farmers (12 million households) [26]. Moreover, all interviewed participants, except the extension workers, indicated to be unaware of these services. The extension workers did not make effective use of digital platforms to deliver services to farmers as planned due to various limitations, including the lack of digital devices and Internet services. Furthermore, the agriculture sector is still dominated by elderly and illiterate people. The study by Guo et al. [27], Zou et al. [28], and the European Commission [29] also reported similar results that the aged population dominates the agriculture sector, which poses a threat to agriculture development. The envisaged FDIS platform could face similar challenges if appropriate implementation measures are not considered, such as stakeholder involvement, awareness campaigning, resources availability and encouraging young people to participate in agribusinesses, to name but a few.

4.2. Toward a Farmers Digital Information System (FDIS)

We are working on an innovative integrated digital system, which is essential to enable farmers' access to services in a complete farming cycle and allow future services to be built upon. Indeed, the comprehensive data on farmers, farms, and other stakeholders contained in the proposed FDIS platform can solve these problems, as current and future services will empower farmers and offer them services throughout the complete farming cycle under one roof. The FDIS will strengthen the existing digital services in the areas of marketing agriculture products, subsidy distribution, and access to credit, insurance, and quality farm inputs to protect the environment and consumers' health. Unlike the current systems, the FDIS will enable extension and advisory services to be coordinated, as experts and consultants will access the comprehensive farmer and farm data for specific advice. Furthermore, it will provide access to all other services around the farmer through a network of agricultural players, such as financial and insurance service providers, input suppliers, agricultural processing industries, and other players throughout the country. Chandra and Collis [30] argued that many developing countries' agriculture sectors face similar challenges. Therefore, although the FDIS platform is designed for a specific country, the platform can be adopted to other lower- and mid-income countries.

4.3. Implications of the Study Findings

The results of this study can contribute to policy development and future e-Government services. We therefore recommend the following:

- e-Government services should involve key stakeholders from the earliest stages of design to understand the social, infrastructural, and environmental contexts for successful and sustainable implementation.
- e-Government services should not be introduced to users unannounced. The government must use its resources to raise awareness and educate users about the importance of these services, while gathering their opinions on the changes.
- Closely examine the working environment, including the availability of digital devices and the cost of Internet for service providers such as extension workers.
- The proposed digital services must be well planned and designed to enable their successful use on existing platforms.
- The government should invest in awareness campaigns to influence the use of e-services and achieve the service objective for targeted stakeholders.
- The government should implement an integrated digital platform with comprehensive data that meet the needs and enables stakeholders' access to all essential services in the complete farming cycle.

4.4. Limitations of the Study

This study focused on the state of e-Government agricultural services in Tanzania. Consequently, digital agricultural services and startups offered to farmers by the private sector were not included in the study. The e-Government agricultural services studied are only available in Tanzania. As there is no evidence of e-Government services for livestock farmers, this study was also limited to Tanzanian's three main cereal crops: maize, paddy, and wheat.

4.5. Future Work

The study examined existing e-Government services and the challenges to be met in order to pave the way for the future integrated platform called FDIS, which will enable stakeholders to access all essential services in a comprehensive way. We will collect the views of all key stakeholders to create a participatory design and assess an enabling environment for FDIS implementation, addressing stakeholders' needs and motivation for successful adoption and use. In the future, the FDIS platform can be integrated with blockchain technology, which looks promising for the evolution of agriculture and sustainable developments in developing countries, as it offers robust mechanisms for securing the various transactions required [31,32].

5. Conclusions

Generally, e-Government services are essential for the development of the agriculture sector through the efficient and effective delivery of services to stakeholders. Despite some difficulties, existing ICT-based services for farmers, particularly DFSDS, have enabled many registered farmers to access government subsidies. Despite some 60 years of government subsidy programs in Tanzania, most registered farmers reported that they were receiving fertilizer subsidies for the first time. Therefore, the system of the manual distribution of subsidies has limited government services and their impacts on farmers and the agriculture sector as a whole. The call center has enabled extension services to be expanded, as most farmers have access to mobile phones that they can call to receive professional advice on best farming practices. However, the challenges posed by the approach to implementing e-Government services, the lack of motivation among extension workers due to a poor working environment, and low stakeholder awareness of existing e-services have all contributed to reducing the impact of e-Government services in Tanzanian agriculture. In addition, the lack of integration between digital e-Government platforms has led to the duplication of efforts and disadvantages in the provision of services to farmers and other stakeholders. As a result, FDIS—a more comprehensive integrated digital platform—is potentially useful for sustainable agriculture in Tanzania and can be adopted in many other developing countries.

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Appendix D

Article IV: Designing a Farmer's Digital Information System for Sustainable Agriculture: The Perspective of Tanzanian Agricultural Stakeholders.

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RESEARCH ARTICLE

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Designing a farmers digital information system for sustainable agriculture: The perspective of Tanzanian agricultural stakeholders

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Abstract

This paper is part of a broader study that aims to design and develop a digital platform that addresses the common challenges of smallholder farmers. More specifically, we analyzed stakeholders' opinions on the farmers' digital information system (FDIS) designed for sustainable agriculture in Tanzania. We used a qualitative research approach to interview 74 key agricultural stakeholders, including the Ministry of Agriculture, the government subsidy office, agricultural insurance companies, financial institutions, farmers, extension agents and agro-dealers in 13 regions of Tanzania. The study findings reveal that most stakeholders could adhere to the FDIS design for sustainable agriculture, as it potentially solves common challenges by enabling access to quality farm inputs, credit and insurance services, subsidies, advisory services, and markets for their products. However, the study identified certain factors that could hinder the full potential of the envisaged system, such as digital illiteracy and poor ICT infrastructures in rural areas. By interviewing key agricultural stakeholders, we confirm the potential of FDIS to make agriculture more sustainable in low- and middle-income countries. The FDIS should therefore contribute to food security, environmental protection, job creation and higher incomes, as the agriculture sector becomes more dynamic once it is localized and adapted to the needs of all agricultural stakeholders. In addition, the government is expected to play a key role in setting up the agricultural stakeholders at a national level to help them overcome the challenges involved in exploiting the full potential of the FDIS.

KEYWORDS
farmers digital information system, information system, smallholder farmers, sustainable agriculture, system design, Tanzania

1 | INTRODUCTION

Smallholder farmers have potential contributions to the Sustainable Development Goals 1 (no poverty), and 2 (zero hunger) as agriculture employs more than one billion people and produces about 70% of the worlds' food (FAO, 2021). Therefore, agriculture is the major source of economic growth and peoples' livelihoods in most low- and middle-income countries including Sub-Saharan Africa. In Tanzania, agriculture employs around

70% of the population and contributes to about 30% of the country's GDP (United States Agency for International Development, 2022). Digital technology is increasingly becoming a tool of production, services and business in all sectors including sustainable agriculture as it increases production efficiency, minimizes cost and somehow protects the environment (Mushi et al., 2022; Saiz-Rubio & Rovira-Más, 2020). Therefore, application of digital technologies in agriculture is essential for the economic development and well-being of the global society.

However, digital technologies for smallholder farmers particularly in low- and middle-income countries could differ from the cutting-edge technology in agriculture mostly used by large scale farmers and developed countries. Qureshi (2015) and Zhang et al. (2021) argued that technological advancement should focus on people's needs and must have impacts in their lives, without copying and pasting technologies from the developed countries. Mushi et al. (2022) assessed the various technologies used in agriculture and ascertained that while smart farming holds promise for sustainable agriculture, it cannot work properly for smallholder farmers, the majority of whom live in rural areas. Furthermore, the existing digital technologies for smallholder farmers lack sustainability and do not meet the needs of farmers in a complete farming cycle (Mushi et al., 2022). A similar study identified 94 agricultural digital services and startups in Tanzania but most of them do not work or are not known to farmers and they don't know how to use them (Hilbeck et al., 2022).

This paper is part of a broader study that aims to design and implement a digital platform for smallholder farmers to access all essential services under one roof. Thus, it contributes to the body of knowledge on the practical design of the Farmers' Digital Information System (FDIS) based on the opinions of stakeholders in the agricultural sector in Tanzania. In previous studies, we conducted a systematic literature review to identify common challenges of smallholder farmers, particularly in Tanzania (Mushi et al., 2022). Next, we developed an abstract design for the FDIS – a platform run by the government or as part of a public-private partnership to enable farmers to access all the essential services in a complete farming cycle, such as credit, insurance, market, subsidy, agro-dealers and advisory services for sustainable agriculture (Mushi, Serugendo, & Burgi, 2023). In addition, we conducted a survey to establish the status of e-government services in the agriculture sector in Tanzania to understand the challenges and opportunities of existing ICT-based services for farmers and other stakeholders (Mushi et al., 2024). Therefore, this study presents an investigation of the challenges raised by key stakeholders in the agricultural sector and their recommendations for refining the FDIS.

2 | LITERATURE REVIEW

Digital technologies are essential production tools in all socio-economic activities, including business, services and industries. However, the adoption and use of ICT differs between organizations, societies, and countries. While some countries and production sectors are adopting the use of cutting-edge technologies thanks to infrastructure, finance, human resources and good policies, others are lagging due to a variety of factors (Mushi, Serugendo, & Burgi, 2023). For instance, smart farming is the latest digital evolution in agriculture, stemming from precision agriculture (Saiz-Rubio & Rovira-Más, 2020). Smart farming and precision agriculture involve the use of most advanced ICTs, such as the Internet of Things (IoTs), sensors, Big Data, decision support systems (DSS), artificial intelligence (AI), integrated farm management information systems (FIM), variable rate technology (VRT) and other autonomous systems (Burlacu et al., 2014; Guerrero et al., 2021; Himesh et al., 2018; Kweon et al., 2013; Onyango et al., 2021; Saiz-Rubio & Rovira-Más, 2020). In addition, precision agriculture uses robotic technology that deploys unmanned aerial vehicles (UAVs) and unmanned ground vehicles (UGVs) to collect real-time data from the farm (Bogue, 2016). These advanced technologies have made it possible to optimize farm inputs, monitor crops and livestock, forecast yields, collaborate with other stakeholders in the supply chain and thus achieve sustainable agriculture – increasing production, income and environmental preservation (Bhakta et al., 2019; Hrustek, 2020).

Although precision agriculture is dominant in northern countries, some developing countries have adopted these digital technologies for sustainable agriculture. For instance, online fertilizer recommendation to farmers in Bangladesh (Hossain & Siddique, 2020). However, the adoption of smart farming and precision agriculture in low- and middle-income countries is still in its infancy (Onyango et al., 2021). Mobile and web-based digital application are the most widely used ICT services in developing countries. Individuals, companies and governments are using this approach to offer products and services to their clients, taking advantage of increased access to mobile devices and internet penetration. Moreover, mobile application such as Unstructured Supplementary Data (USSD), which run on the network and not on the user's device, and therefore don't need to be installed on the user's phone, are simple to implement and use in regions faced with digital illiteracy and limited infrastructure. For example, the Kenyan Agriculture and Livestock Research Organization's (KALRO) mobile applications project for different value chains (FAO, 2018), and the Association for People of Haryana's (AFPOH) e-governance mediated agriculture project in India (Behera et al., 2015). Apart from e-government agriculture services, digital start-ups and companies have emerged to exploit the commercial potential of the agriculture sector. Examples include "Tru Trade" in Uganda, "eSoko" in Ghana and "mFarming" in Kenya, Ghana and Tanzania (Hamill, 2017), eKichabi mobile service, a digital telephone directory linking agricultural businesses to improve the marketing of agricultural products in Tanzania (Ananditha et al., 2024).

A recent study in Tanzania alone revealed the existence of 94 digital services and startups in the agriculture sector (Hilbeck et al., 2022). However, these digital services and startups face various challenges due to the lack of a complete solution to farmer's needs, lack of sustainability and duplication of services. Hilbeck et al. (2022) concluded that most digital services were inactive, unknown and unused by agricultural stakeholders. Furthermore, a survey conducted in Tanzania to determine the state e-government services in the agriculture sector revealed the government's strong determination to digitize agricultural activities and services for development (Mushi et al., 2024). However, the results show that existing services lack a common service framework for more comprehensive digital solutions that meet the needs of farmers and other stakeholders as part of a complete farming cycle.

3 | METHODOLOGY

3.1 | General methodology

The study is backed by design science research (DSR) and participatory system design methodologies, with users actively engaged in the design, testing, implementation, and assessment of the system (Barakabitze et al., 2017; Hevner et al., 2004; Peffers et al., 2007). Moreover, the agroecological principles for successful digitalization require user involvement to contribute to knowledge and express their needs from the designing stage (Hilbeck et al., 2022). DSR is a general approach of the large study on designing FDIS for sustainable agriculture in Tanzania. We customized a DSR process developed by Peffers et al. (2007) to eight steps namely; problem identification, requirements, preliminary design, user survey, refined artifact design, implementation, evaluation and communication. The highlighted fourth (user survey) and fifth (refined artifact design) steps in Figure 1 below present the findings of this paper.

We conducted a problem identification through a literature review focusing on challenges of smallholder farmers and the use of digital technologies for sustainable agriculture (Mushi et al., 2022). We then developed requirements and designed a preliminary artifact of farmers digital information system (FDIS) – a platform that could solve challenges of smallholder farmers in a complete farming cycle, see Figure 2. Therefore, we conducted a user survey to orient the preliminary design to potential stakeholders and collect their opinions and requirements for a refined artifact.

3.2 | User survey methodology

We used a qualitative research approach and case study design to explore the opinions of agricultural stakeholders on the designed FDIS to address common challenges across the entire farming cycle for sustainable agriculture. The study's approach provided an insight into the challenges faced by the agricultural sector, introduced the design of the FDIS and how the envisaged platform will improve agricultural activities. We conducted interviews to 74 agricultural stakeholders: two (2) heads of divisions and one (1) head of unit at the Ministry of Agriculture (MoA), three (3) agricultural insurance companies, six (6) agriculture credit service providers (financial institutions), 20 cereal crops farmers (maize, wheat and paddy), 12 livestock keepers (cattle and goats), nine (9) agro-dealers, 12 extension workers, and nine (9) customers (processing industries and consumers). We selected the stakeholders from 13 regions in Tanzania: Rukwa, Mbeya, Morogoro, Ruvuma, Iringa, Tanga, Manyara, Mjini Magharibi, Kaskazini Pemba and Kusini Pemba (cereal crops and livestock high producing regions), Dar es Salaam, Arusha and Dodoma (major consumers and processing industries). We used purposive sampling to select participants with information relevant to the study (Robinson, 2014). Purposive sampling was used to select participants from the MoA, agricultural credit and insurance services companies, extension workers and processing industries. While simple random sampling technique was used to select crop farmers, livestock keepers, agro-dealers and customers.

In-depth semi-structured interviews enabled participants to explain in detail current practices, challenges and how FDIS intervention could make agriculture more dynamic. We took note to record the conversations and read the answers provided to the participants for review at the

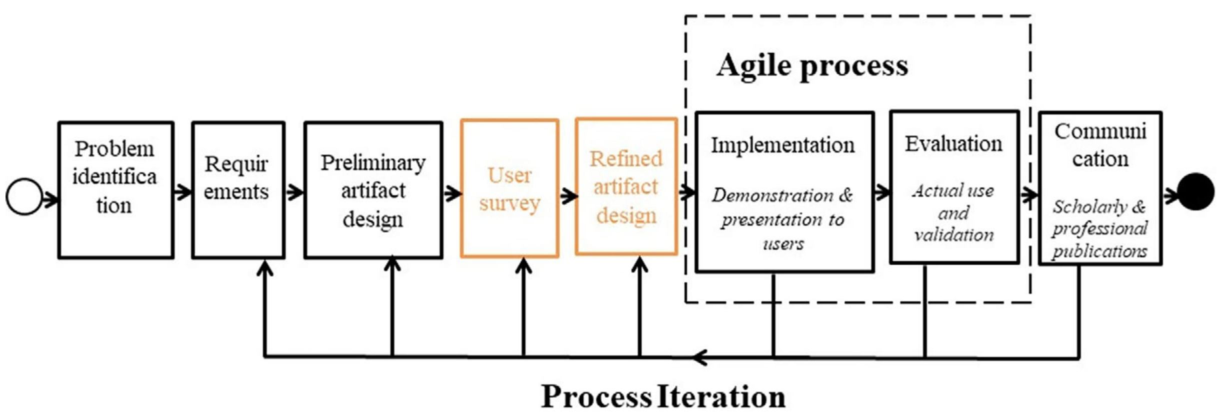

FIGURE 1 DSR Method (Mushi, Serugendo, & Burgi, 2023).

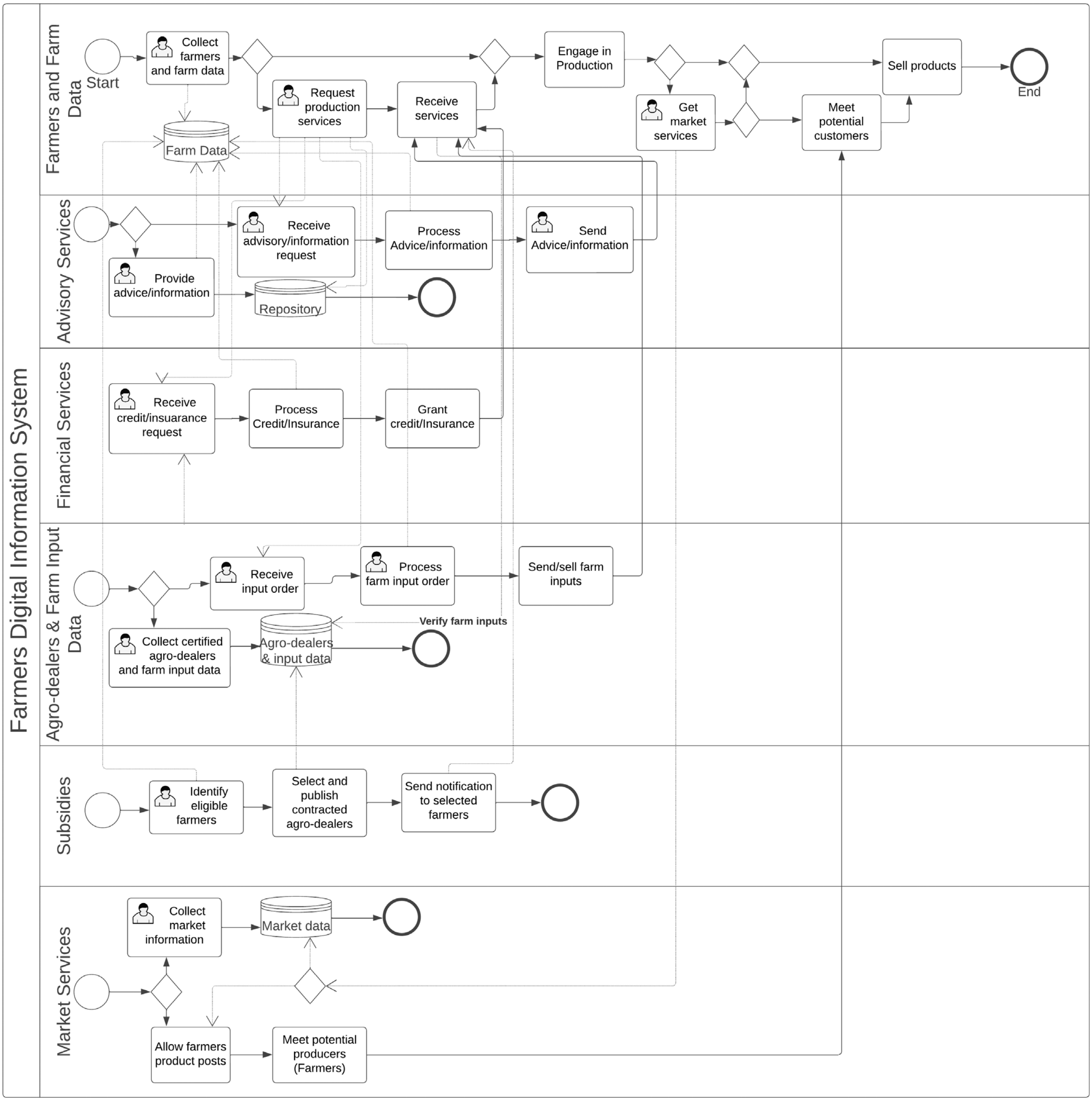

FIGURE 2 FDIS preliminary design BPMN diagram (Mushi, Serugendo, & Burgi, 2023).

end of the conversation, to ensure the reliability of the data. We then analyzed the data using thematic data analysis (Mihas, 2023), coded the transcripts and established different categories and subcategories (selected based on stakeholders' raised opinions) represented in the data. Therefore, we have established themes that cut across the data categories and reflect the key issues emerging from the data. We extracted and included direct quotes from the participants to highlight key points of the study objectives.

4 | FINDINGS

We present the study findings in the following themes: stakeholders' current practices, challenges, and opinions on the FDIS design intervention, and capabilities and infrastructure for FDIS operations. We conducted a comparative analysis among various variables. We assigned codes to the participants as follows: A series (A1, A2…) for agro-dealers, F series (F1, F2…) for crops farmers, L series (L1, L2…) for livestock keepers, C series

(C1, C2…) for credit service providers, E series (E1, E2…) for extension workers, CS series (CS1, CS2…) for customers, and AI series (AI_1, AI_2…) for agricultural insurance service providers, while […] stands for skipped words in the direct quotes.

4.1 | Stakeholders' current practices, challenges, and opinions on the FDIS design

The study explored the practices, challenges, and opinions of all stakeholders on the design of FDIS as an intervention in the agricultural value chain in Tanzania.

4.1.1 | Agro-dealers

Agro-dealers are critical stakeholders in agriculture as they determine the distribution, access and use of quality farm inputs and equipment. The availability of sub-standard farm inputs which are harmful to the environment and peoples' health, rises the need for registered agro-dealers to have access to information on the authorized and banned inputs from the responsible authorities. However, the findings indicate that agro-dealers do not have access to the information from the authorities but rather take other measures such as buying inputs from the reputable manufactures and importers, and shared information from other agro-dealers. Agro-dealers have indicated that the obstacle to accessing information is lack of knowledge of the source and difficulty in gaining access to the responsible authorities. All agro-dealers admitted that their services were focused on urban areas for commercial reasons, which partly explains why most smallholder farmers in rural areas do not have access to, or use, modern farm inputs and equipment.

> "[…] as an agro-dealer you can't invest in remote areas where the market is smaller. In urban, you can sale to many farmers coming from all directions throughout the year while in rural areas the sales will be seasonal" (A5, Mbeya).

Table 1 presents the summary of agro-dealers challenges and opinions on the envisaged platform.

While a few agro-dealers couldn't foresee the challenges of the envisaged platform, most identified illiteracy, and poor digital skills as the major anticipated barriers. Other possible barriers mentioned are rejection of technology, with many smallholder farmers being too old to accept, learn and use digital technologies. The assertions that most farmers are too old are verified by the demographics of this study (Table 2). It shows that 38% and 41% of the surveyed smallholder farmers are aged above 50 and 60 years, respectively. Agro-dealers have indicated that they have digital literacy skills and own digital devices, so they will only need training on the envisaged platform. Agro-dealers have been asked to modify the design of FDIS by deleting or adding certain functionalities that will solve their current problems. They suggested that FDIS should include additional functionality for transport services provided by logistics companies. The aim is to resolve the current difficulties associated with finding transport services for inputs from manufactures or importers to different parts of the country. For example, an agro-dealer involved in the distribution of government subsidies for fertilizers reported having spent more than 2 weeks looking for transport services between the manufacturer in Dar es Salaam and the Mbeya region. Apart from modifying the design of the FDIS, agro-dealers suggested improving rural infrastructure, such as a reliable road network and telecommunication, following the example of the rural electrification project currently underway in the country.

TABLE 1 A summary of agro-dealers challenges and opinions on FDIS design.

Challenges	Opinions on FDIS design	Refining FDIS design
Poor access to information from agro-inputs standards regulatory authorities	FDIS as a link to sources of input information from the authorities and could help prevent the sale of unregistered and banned inputs	A5, Mbeya proposed the logistics services to solve the challenge of inputs transportation
Availability of unregistered agro-dealers	Digitizing the supply of agro-inputs cannot automatically eliminate unregistered agro-dealers	
Low farmers´ purchasing power in rural areas	Ability for online payment gives possibility for input delivery services in rural areas	
Most farmers are aging out	FDIS can help agro-dealers to provide precise inputs and advisory services	
Low literacy to adopt modern farming techniques		
Poor logistics services in agro-inputs supply		

Source: Mushi, Burgi, and Di Marzo (2023).

TABLE 2 Demographic characteristics of farmers ($N = 34$).

Variable	Category	Frequency (*N*)	(%)
Location (Regions)	Tanga	5	14
	Morogoro	2	6
	Mbeya	4	12
	Manyara	5	14
	Iringa	3	9
	Ruvuma	2	6
	Rukwa	4	12
	Kusini Pemba	2	6
	Kaskazini Pemba	2	6
	Mjini Magharibi	2	6
	Arusha	3	9
Location status (Ward level)	Rural	24	70
	Semi-urban	7	21
	Urban	3	9
Gender	Male	25	74
	Female	9	26
Age group (Years)	21–30	3	9
	31–40	4	12
	41–50	13	38
	51–60	11	32
	61 and above	3	9
Educational level	No formal education	2	6
	Primary education	25	73
	Secondary education	6	18
	Diploma	1	3
Farming activity (Occupation)	Maize farming	9	26
	Rice (paddy) farming	8	24
	Wheat farming	5	14
	Dairy cattle keeping	7	21
	Indigenous cattle keeping	4	12
	Goats keeping	1	3
Farm size	Below 3 hectares	1	5
	4–6 hectares	14	64
	7–9 hectares	7	31
	Below 5 livestock	2	17
	6–10 livestock	7	58
	11–15 livestock	1	8
	16 and above livestock	2	17

Source: Mushi, Burgi, and Di Marzo (2023).

4.1.2 | Farmers

Farmers play a central role in the agricultural value chain as they produce food and raw materials and consumes farm inputs and other services such as credit and insurance necessary for production. This study investigated both crop farmers and livestock keepers by selecting three major cereal crops (maize, paddy, and wheat) and three major livestock (dairy cattle, indigenous cattle and goats) in Tanzania (see Table 2). The survey mainly explored their current practices and challenges across the farming cycle and their views on FDIS intervention to improve their practices to increase production, income, and environmental protection.

The majority farmers use experience inherited from parents, the community, and other farmers in most of their activities. For instance, farmers reported using simple tools such as the hand hoe for land preparations, but a few reported using tractors and other simple machinery. Crop farmers reported a lack of soil health testing and expert advice on land preparation. Similarly, livestock farmers reported a lack of knowledge and resources for the preparation of modern animal shelters and the selection of quality breeds for production. Although many farmers (31, 91%) indicated that they did not have the services they needed to prepare their farms, a few (3, 9%) said they had received regular training from non-governmental organizations (NGOs). In other places, manufacturers of inputs, particularly fertilizers and seeds, have been involved in training farmers through model farms.

The results reveal that 23 (68%) of crop farmers use local seeds selected from previous harvest, and 7 (19%) use quality seed, while 4 (13%) uses both local seed and quality seed from agro-dealers. Although local or informal seeds system comply with agroecology principles, studies show that they are subjected to low quality and production compare to quality certified formal seeds (Biemond, 2013; Louwaars & Manicad, 2022). Farmers cited the lack of investment capital to purchase and apply modern inputs as a barrier to increasing production. On the other hand, dairy livestock keepers indicated that the lack of knowledge and the absence of reliable sources of dairy cattle breeds force them to use breeds available from other farmers on the advice of their fellow farmers. Dairy cattle keepers claim that the breeds available are not pure and that their yield are low in relation to expected production. Moreover, farmers identified other difficulties linked to farm preparation, access to quality inputs and production management. These include remoteness of agro-dealers, the high cost of inputs, substandard seeds and of the latter, particularly for wheat growers.

This study collected farmers' opinions on the design of the FDIS intervention over the course of an entire farming cycle (see Table 3). Most farmers (30, 88%) indicated that they would agree to use FDIS – the platform that will collect and enable farmers to share their data with other stakeholders to obtain services. Farmers mentioned that the FDIS platform will enable access to essential services from other stakeholders from the early stages of farm preparations to post-harvest activities. However, 4 (12%) farmers rejected the idea of digitizing the agricultural value chain as conceived by FDIS. Overall, farmers believe that the envisaged FDIS platform will have a considerable impact and change their current practices to increase production and income.

4.1.3 | Credit services providers

Financial institutions are essential stakeholders in agriculture value chain as they provide credit services to other stakeholders for investment. This study investigated current interactions and challenges between financial institutions and smallholder farmers. The study introduced FDIS to credit service providers and collected their views on improving credit services to smallholder farmers. We interviewed six commercial banks located in different regions of agricultural production. However, only one community bank was physically operating in rural area, the others were in urban areas. Four credit service providers indicated that they granted loans in cash and farm implements, while two indicated that they only granted cash loans.

TABLE 3 A summary of farmers challenges and opinions on FDIS design.

Challenges	Opinions on FDIS design	Refining FDIS design
Lack of modern farming knowledge and use of simple farm tools	FDIS could add value to their knowledge and improve or change practices in farm production	Information about warehouse services for storing farm harvests Logistics services to solve the challenge of farm products transportation Ability to request different permits from the authorities. Example: harvesting permit and farm products transportation or exportation permit
Farmers do not have access to agricultural insurance and credit services Use of low-quality farm inputs such as seeds and fertilizer	FDIS could link farmers to insurance and credit service providers for access to sufficient investment capital and develop their farms for increase product and income	
Crop farmers depend on rainfall for irrigation while using experience to predict rain season	FDIS will help access to reliable weather information for precise rainfall forecasting to reduce the risk of losing crops to droughts or floods	
Smallholder farmers depend on intermediaries (middlemen) to sell their produce. This system is exploitative to farmers as it forces lower price to farm products	Farmers indicated FDIS could be a source of market information and platform to market their products. Thus, could help eliminate the middlemen in the value chain as farmers could directly meet the potential buyers and sell at a better price	
Substandard inputs in the market results to poor production	Farmers could identify certified agro-dealers and verify farm inputs authenticity	

Source: Mushi, Burgi, and Di Marzo (2023).

The findings reveal that financial institutions provide credit services to farmers, but there are a series of conditions for smallholder farmers. For example, one of the financial institutions mentioned that it would only provide credit services to farmers who use an irrigation system and whose crops have a stable market, to avoid risking the loan. The study also revealed that financial institutions grant personal loans to large and medium-sized farmers, while smallholder farmers are forced to form farmers' groups or associations to access credit services.

> "The large and medium sized are eligible for personal loans but smallholder farmers must organize themselves in groups to achieve collective responsibility in loan recovery, thus, avoiding risks" (C6, Ruvuma).

Financial institutions indicated the rate of smallholder farmers' access to credit services as generally low and majority have no access to the service in the country.

The study of the conditions for applying credit services to farmers revealed that the information and documents required are personal information with identities, land documents and ownership status, the farm business plan (types of crops, irrigation condition, etc.), or other asserts held by the farmer and documents, loan history and farm production and sales records. For farmers' groups or associations, the conditions are the affirmation of group members and operating contracts (in case of contract farming). The findings also reveal that many credit service providers require collateral such as land and property titles and vehicle registration documents. However, one of the financial institutions indicated that requiring collateral is not always the case for smallholder farmers.

> […] "we consider the good crop structure with a well-defined value chain particularly contract farming. We have issued around 7.8 billion Tanzanian shillings to farmers without any collateral. On the other hand, farm tools loaned to farmers are used as a collateral" (C4, Dar es Salaam).

However, the study found that not only has contract farming improved lending conditions for smallholder farmers, but so have guarantors such as Tanzania Agricultural Development Bank (TADB), which guarantees farmers up to 50% of their income. Meanwhile, in other parts of the country, the farm itself stands as a collateral due to its high value, thus, smallholders do not need to submit other asserts. The findings show that many financial institutions cited the demand for collateral as a barrier for most smallholder farmers who cannot meet loan eligibility criteria. Some credit service providers mentioned smallholder farmers' lack of education about loans, their poor knowledge of loan conditions, such as strictly improved conditions.

> […] "many farmers are not aware of the loan education; they don't know that even without house or land title deeds one can get credit service. Indeed, commercial banks are agencies of the Tanzania Agricultural Development Bank, which provides a 50% guarantee and the remaining 50% is borne by the farmers, but we may cover up to 75% loan guarantee to other farmers thus they don't need strong conditions to cover the remaining 25%" (C6, Ruvuma).

Other barriers to smallholder farmers' access to credit services are mentioned: weak credit services in rural areas, refusal of service due to high production risks, such as dependence on seasonal rainfall, and poor market conditions for some crops.

Focusing on the challenges of financial institutions' relations with smallholder farmers, the findings reveal that credit service providers have many times struggled to recover loans after smallholder farmers failed to repay. The mentioned reasons for the failure are mismanagement of loans based on the farm business plan, particularly using loans for purposes other than agriculture. However, other farmers are unable to repay for valid reasons, such as poor market crop conditions and production losses due to floods, drought, pests and disease. The study shows that smallholder farmers have a "bad character" because they hide important information or cheat financial institutions when assessing a loan. For instance, if a farmer presents someone else's land ownership documents as his own when applying for a loan, the financial institution will notice this when it comes to loan collection problems. One of the financial institutions indicated that some of the challenges such as farmers use of loan for other purposes and fail to repay might have been caused by credit service providers, as they take long time to process loans for the farmers. For example, a farmer receives a loan when important early-stage activities, such as land preparations and planting have already passed, so the loan will not be used as intended. Financial institutions have identified other challenges to the provision of credit services to smallholder farmers in Tanzania: few institutions provide financial services to farmers under rigid conditions, loan processing costs are high, the agriculture sector is neither formalized and nor dynamic, and the majority of smallholder farmers lack collateral and are not involved in a well-structured crops value chain.

The findings reveal that financial institutions could accept the idea of the FDIS with opinions that the envisaged platform will solve many of the challenges in providing credit services to smallholder farmers. Financial institutions managers claimed that the comprehensive farmer data contained in the envisaged platform is essential for minimizing the risks involved in lending to smallholder farmers, but it will also help financial institutions to process and grant loans in a timely manner, as soon as the data becomes available. The findings show that three financial institutions managers indicated that it is not currently possible to receive applications and grant loans entirely online on the FDIS platform, while two indicated that it was possible, and one mentioned the first loan application should be face-to-face and that subsequent applications could be made entirely online. When asked whether financial institutions access to farmers' comprehensive data in the FDIS could replace the demand for collateral to enable many farmers to access to credit services, four institutions managers indicated that data could not replace the demand for collateral, while two mentioned that access to data could influence the assessment of farmers using criteria other than collateral, such as house titles.

> "The issue is not access to data; humans are subjected to 'character change' thus, collateral is the last resort. Data is used to issue loans while collateral is useful for loan recovery" (C5, Iringa).

While many financial institutions managers indicated that access to data alone cannot replace request for collateral, one financial institution manager mentioned that a well-structured crop value chain, particularly under "contract farming," is enough to issue credit service to smallholder farmers without demanding collateral. The findings reveal that financial institutions have the opinion that the FDIS could be useful to their institutions and could eliminate many challenges of smallholder farmers access to credit services. They pointed out that access to data of other stakeholders, such as processing industries and agro-dealers on the FDIS platform could make the agriculture sector more dynamic, as they already have good business relations. The identified anticipated challenges of the envisaged system by financial institutions include network problems, which they face even in the current banking system, cyber-security issues, lack of cooperation from other key stakeholders, and quality of data. The study found that the identified major strength of the FDIS platform is the collection of comprehensive data on the farmers and other stakeholder, which can be shared for access to services, but could also better formalize the agricultural sector. In modifying the design of the FDIS, financial institutions suggested that the envisaged system record the history of loans granted to farmers, add important stakeholders such as TADB, and a scorecard system showing the likelihood of farmers receiving credit services based on the quality of data entered to the platform.

4.1.4 | Customers

Customers play a key role in the agriculture value chain, as they determine the market and the income of farmers and other stakeholders. In this study, customers refer to the processing industries that buy agricultural products from farmers as raw materials, and domestic customers who buy agricultural products from farmers for consumption. We interviewed a total of nine customers, four managers of the processing industries and five domestic customers in different regions in Tanzania.

The findings reveal that customers collectively could accept the design of FDIS and would use the envisaged platform to buy directly from the farmers. The customers have the opinions that buying directly from farmers through the FDIS will add great value to all parties. One of the processing industry managers mentioned that FDIS will help processing industries to get information from farmers such as crop products, location, price and quantity of the farm products, at the right time and at a reasonable cost. Moreover, customers have the opinion that FDIS will reduce cost of acquiring farm products while increasing income to farmers through better prices compared to existing value chain, which involves intermediaries. All the interviewed customers believe that FDIS will promote agricultural development in several ways, including eliminating middlemen in the value chain, increasing farmers' incomes and encouraging investment and production on farms, and reducing the cost of production for processing industries and, ultimately, for end consumers. In addition, the planned platform will provide an important link between farmers and processing industries:

> [...] "the platform is the bridge between farmers and other stakeholders. The stakeholders' network has the following advantages. 1) Processing industries can directly communicate with farmers on the standards required for production contrary to current situation where farmers produce at the standards not needed by the industries and market. 2) The linkage can also inform farmers of types of crops they should grow based on the market needs" (CS_1, Arusha).

Moreover, the findings show that customers collectively have the opinion that eliminating the intermediaries in the agricultural value chain by buying directly from farmers through FDIS will reduce the price of farm commodities as raw materials and stabilize market prices for farm products. The findings identified bank transfers and mobile money as the preferred method of payment by customers to farmers in the envisaged digital platform. Investigating the anticipated challenges to the envisaged platform, the findings reveal that customers mentioned infrastructure issues, particularly Internet service in rural areas, poor digital literacy with the majority of farmers being too old, and costs of the Internet bandwidth.

4.1.5 | Agricultural insurance services

This study interviewed three directors of the agricultural insurance service providers: two of them offer insurance for both crops and livestock, and the third offers only crop insurance. The directors of the insurance service companies have indicated that they provide services to individual farmers or groups of farmers. The findings reveal that insurance services are essential to cover the various risks associated with agricultural production. Identified risk covered by agricultural insurance companies include climatic risks such as floods, droughts, and hail, the vegetation index, pest and diseases, theft, and fire outbreak. The covered risks in livestock production are sudden death, forced slaughter, and diseases out of farmer control. On the other hand, the findings show that insurance service providers offer different packages to their clients. One of them offers two main packages: input coverage, which only covers the cost of inputs, and production coverage, also known as area index, which is a comprehensive insurance policy covering all production risks. Another insurance company offered four different packages: the meteorological index, which covers weather-related risks, the soil moisture index, the surface yield index and the multi-risk crop insurance, which covers all risks related to farm production. Moreover, the study findings reveal that the surface index cover is the most widely purchased agricultural insurance from all service providers.

Insurance service providers collectively felt that farmers' access to insurance services was low due to a lack of awareness and income. Insurance companies provided an estimated number of active agricultural insurance subscribers, as shown in Table 4.

The study showed that insurance companies collect information on agricultural production using a survey form that gathers information on the farmer, production and loss history, farm size, location and crop types. Other insurance company works with extension officers to collect this information and farmers' yield expectations. We also found that insurance companies work closely with weather and agricultural data companies, particularly "ACRE Africa" to get the weather index information for evaluation of related risks in different locations. Therefore, insurance service providers do visit the farm or livestock to identify potential risks and advice the farmer on the appropriate insurance package. The findings show that all insurance service providers have had the experience of compensating farmers who have lost production due to climatic hazards (drought, floods, and hail) and farm invasions by wild animals. Further findings on the current challenges and opinions on the FDIS design are presented in Table 5 below.

Indeed, the insurance service providers have ascertained that the envisaged FDIS platform has the potential to eliminate most of the challenges of smallholder farmers' subscription to insurance services. However, it will require cooperation of other stakeholders, such as financial institutions and government agencies. Moreover, agriculture insurance should be added in higher education curriculum to produce experts in this service sector. Insurance service providers mentioned having relationships with other stakeholders such as agro-dealers, processing, and farm input industries, which reinforces the idea that FDIS could extend the services to help smallholder farmers become part of this agricultural stakeholders' eco-system and make the agriculture sector more dynamic. However, insurance providers are anticipating that using the envisaged platform will bring new charges, which could increase the costs of operation and of the technical infrastructure.

TABLE 4 Agricultural insurance subscribers.

Insurance company code	Years of experience	Estimated active subscribers in Tanzania
AI_1	9	40,000
AI_2	8	30,000
AI_3	11	26,000

Source: Mushi, Burgi, and Di Marzo (2023).

TABLE 5 A summary of insurance service providers challenges and opinions on FDIS design.

Challenges	Opinions on FDIS design	Refining FDIS design
Farmers low awareness and lack of education about agricultural insurance leading to low use of the service	Availability of all services in one platform (FDIS) could increase farmers awareness and usage of insurance service	FDIS should link the farmers' insurance subscription information between companies to avoid fraud and duplication
Lack of agricultural data	FDIS could fill data gaps, which is essential for providing services to farmers	FDIS should integrate important stakeholders, such as the "ACRE Africa" company, which provides agricultural and weather data
High risk of fraud		
High cost of operation and low purchasing power of farmers	FDIS bridging the existing data gaps could influence the design of new affordable insurance packages or provide customizable packages to farmers	
Lack of government support such as insurance subsidies and makes the service compulsory to farmers		
Lack of agricultural insurance experts (no formal training is offered in the country)		

Source: Mushi, Burgi, and Di Marzo (2023).

4.1.6 | Extension workers

Extension workers are key stakeholders in the Tanzania agricultural system because they disseminate the agricultural advisory and expertise services, enact government policies and actions for improving the sector production and the quality of products. In this study, the extension workers refer to agriculture experts employed by the government to work in contact with farmers and who offer their expertise and advisory services to crop farmers and livestock keepers. The interviewed extension workers in different parts of Tanzania had different experiences, some offering exclusively expertise in crop farming or livestock keeping, while others offering both (see Table 6 below for more details).

Investigating existing digital means of reaching farmers, the findings reveal that the majority of extension workers have been by chance introduced to "Mobile Kilimo" (M-Kilimo) – a government-owned mobile and web-based application for services to farmers and other stakeholders. However, most of them have not used the application due to a lack of digital devices, the high cost of Internet, and the absence of government support. The other mentioned digital means that extension workers have been using to reach farmers are WhatsApp and standard mobile communication.

> "We were once introduced to M-Kilimo, managed by the Ministry of Agriculture. But the system failed to work, and I am not using it anymore. When I send SMS to farmers are not delivered, should it be functioning, I could use it because I already introduced the

TABLE 6 Demographic data of extension workers ($N = 12$).

Variable	Category	Frequency (*N*)	(%)
Location (District, Region)	Handeni, Tanga	1	8.3
	Ifakara, Morogoro	1	8.3
	Mbeya council, Mbeya	1	8.3
	Babati, Manyara	2	17
	Iringa council, Iringa	1	8.3
	Songea, Ruvuma	1	8.3
	Mollo, Rukwa	1	8.3
	Ng'ombeni, Kusini Pemba	1	8.3
	Wete, Kaskazini Pemba	1	8.3
	Cheju, Mjini Magharibi	1	8.3
	Arumeru, Arusha	1	8.3
Location status (Ward level)	Rural	8	67
	Semi-urban	4	33
	Urban	0	0
Gender	Male	8	67
	Female	4	33
Age group (Years)	20–29	0	0
	30–39	9	75
	40–49	3	25
	50–59	0	0
Agricultural educational level	Certificate	0	0
	Diploma	12	100
	Bachelor's degree	0	0
Agricultural service category (Occupation)	Crop farming advisory service	3	25
	Livestock management advisory services	4	33
	Both crop farming and livestock management advisory services	5	42
Working experience (Years)	Below 5	1	10
	6–10	5	40
	11–15	6	50

Source: Mushi, Burgi, and Di Marzo (2023).

system to the farmers who were very interested, and I enjoyed helping farmers digitally at any time. After it collapsed, I decided to create a WhatsApp group to keep the service alive. But I also use normal SMS and phone calls" (E4, Manyara).

Other findings show that many extension workers are unable to visit and respond to farmers' emergencies due to a lack of transport, which is a major challenge given they must serve many households scattered in remote areas. Other challenges are the reluctance of farmers to seek and use information and knowledge from experts, and livestock farmers who don't allow experts to visit their farms. Table 7 below summarizes the extension workers challenges and opinions of FDIS design.

In introducing the FDIS design, the findings reveal that extension workers collectively accepted the idea and could use the envisaged platform. However, extension workers anticipate that farmers' digital illiteracy, poor infrastructure, particularly in rural areas, and cost of Internet bandwidth will be important barriers to the envisaged FDIS platform, in addition to poor working condition such as lack of access to digital devices. In general, it was stated that having access to extensive data in the proposed system would represent a significant advancement in addressing the challenges encountered when collaborating with farmers and other stakeholders.

4.1.7 | Ministry of Agriculture

The Ministry of Agriculture (MoA) in Tanzania plays a central role for developing policies, controlling manufactured and imported agro-inputs, controlling, and monitoring the market of agricultural products, particularly the exportation of food crops and enabling smallholder farmers to engage in increasing the production via subsidy programs. Therefore, the MoA coordinates the activities and works with all key stakeholders to promote the agricultural development. This study interviewed two heads of division – the Crop Development Division, the Agricultural Training, Extension Services and Research Division – and one head of unit – the Information and Communication Technology Unit – within the MoA in Tanzania.

This study ascertained that the MoA has established digital services for farmers in an effort to promote a sustainable agriculture. Those services are the M-Kilimo application, a call center for extension services, and the Digital Fertilizer Subsidy Distribution System (DFSDS). Introducing the FDIS design to the MoA reveals that the envisaged platform has complementary features and will solve a wider range of challenges compared to the currently proposed services.

> […] "Based on your explanation of the FDIS system, we are yet to have a system with all such features especially bringing together all agriculture stakeholders in the country, but we hope we will improve to reach that level of the envisaged system" (MoA, Dodoma).

On the other hand, the MoA mentioned that the government and its agencies involved in the agriculture sector is ready and willing to adopt any essential new suggestions to improve the existing systems. The MoA emphasized that the envisaged platform could be an opportunity for all agricultural stakeholders in the value chain, as it could enable transparent collaborations and services, rendering the agriculture sector even more dynamic. Table 8 below presents MoA ICT related services to farmers and statistics of usage.

The findings reveal that the government through the MoA has the capabilities of adopting and providing all resources required to sustain the envisaged FDIS platform.

TABLE 7 A summary of extension workers challenges and opinions on FDIS design.

Challenges	Opinions on FDIS design	Refining FDIS design
Large number of farmers per one extension worker (an average ratio of one to two thousand)	FDIS platform will simplify the farmers' access to extension workers' services in a flexible and timely manner	FDIS should enable working offline to allow extension services in poor infrastructure areas
Difficult to provide farm specific advisory services	Possibility of farm specific advisory, distance service, and respond to emergencies such as request for animal treatment, pests, and diseases outbreaks. as FDIS could provide access to farm and livestock data	
Lack of transport in scattered farming population in rural areas		
Poor motivation due to difficult working condition such as lack of digital devices and Internet service		

Source: Mushi, Burgi, and Di Marzo (2023).

"Since we already have sections dealing with extension services and digital application system in place and functioning, we will be able to adopt and sustain the envisaged system which looks more of improving the existing systems" (MoA, Dodoma).

The MoA has the opinion that the FDIS design is in-line with the recent launched government project called "Building Better Tomorrow – Youth Initiative for Agribusiness (2022–2030)." Thus, implementing the envisaged platform could attract young workers in the agri-business by providing them with innovative services to all stakeholders with the aim to increase production and income.

The MoA recommended adding some features to the FDIS, such as transportation services from logistics companies, farmers, and farmers' associations access to the international market, rent a storage space in warehouses, and the ability to request and receive different government permits such as crop harvesting, and exportation permits. The MoA added that the FDIS platform should be able to distribute all kind of subsidies such as fertilizer, seeds, implements, and other farm inputs. However, the existing digital services proposed by the MoA face several challenges, which will also be present in the envisaged system: poor support and lack of motivation to extension workers, high cost of the Internet services, poor infrastructure in some rural areas and a high level of digital illiteracy.

4.2 | Capabilities and infrastructure for FDIS operations

A successful implementation and sustainability of a digital platform requires not only stakeholders' willingness to use it, but also capabilities to operate the infrastructure and services. Generally, the findings reveal that agricultural stakeholders could accept the FDIS design and would use the envisaged platform. This study also investigated the required capabilities for implementing and sustaining the envisaged FDIS platform. Capabilities refer to skilled human resources, stakeholders' digital literacy, and financial resources, while the infrastructure focuses on the availability of telecommunication networks, the Internet services, and electricity (Figure 3).

The findings show that with the exception of farmers, all stakeholders (agro-dealers, insurance and credit services providers, extension workers and customers) have the skills to use digital devices such as smartphones, tablets, and computers. These stakeholders indicated to have access to electric power, the ability to purchase Internet services, and consequently could use the envisaged system with minimal training. On the other hand, farmers lack several competencies and physical accesses to the needed digital devices (smartphones, tablets, and computers) for using digital services, as shown in Figure 1.

However, the findings reveal that farmers are able and willing to purchase the required digital devices and are ready to learn how to use them for accessing the envisaged FDIS platform. The on-going rural electrification project conducted by the Tanzanian government, as well as the development of the telecommunication and Internet networks in remote areas are promising. Moreover, most farmers indicated that their preferred service in the FDIS design is the access to credit services, which are essential to invest in modern implements and inputs to boost their

TABLE 8 Ministry of Agriculture ICT based services.

Name of the platform	When launched	Registered stakeholders		Types of services	Usage statistics
M-Kilimo application	May, 2020	Farmers	7,269,106	Market and price information, selling and buying, advisory services and feedback	Number of consultations (advisory services) 75,623
		Extension workers & experts	9985		
		Customers	24,523		
		Agricultural products sellers	26,927		Replied queries 73,839
Digital Fertilizer Subsidy Distribution System (DFSDS)	September, 2022	Farmers	2,828,300	Manage distribution and access of subsidies to farmers	Over 350,000 farmers had received subsidized fertilizer
		Importers	29		
		Manufacturers	3		
		Agro-dealers	3181		
A Call Center	July, 2022	All agricultural stakeholders are encouraged to call for suggestions, complains, request information or seek professional advice		Stakeholders can ask anything in agriculture sector such as issues with the crops, livestock, fishing, marketing, agro-inputs, etc.	Total calls: 5202 Calls back: 2301

Source: Mushi, Burgi, and Di Marzo (2023).

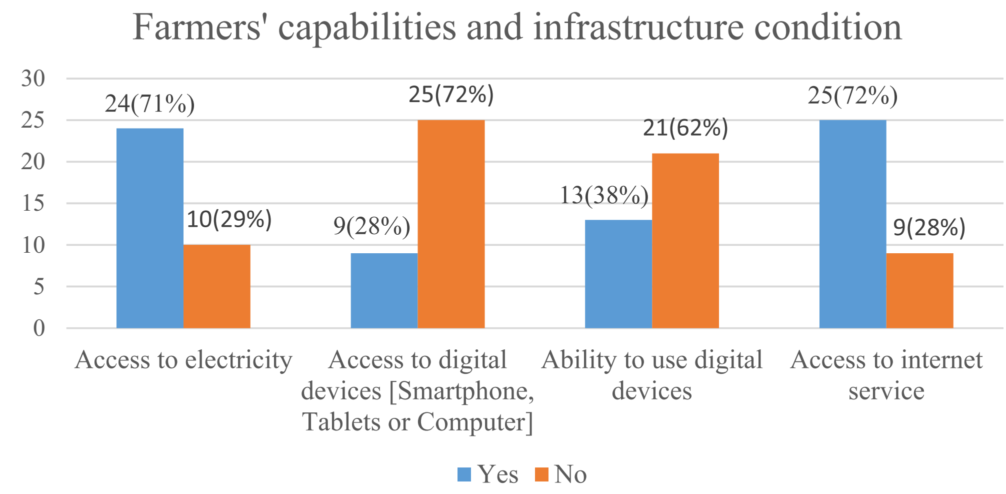

FIGURE 3 Farmers' capabilities and access to infrastructure ($N = 34$).

agricultural production. Other mentioned nice-to-have services include the access to information and advisory services to adopt modern farming knowledge, the insurance services, market, and market information for obtaining better prices for their agricultural products. Generally, farmers indicated that the envisaged FDIS platform that as key to coordinate the activities of the farmers and other stakeholders, which is deemed as essential for increasing the agricultural production.

5 | DISCUSSION

This study presents stakeholders' opinions on the challenges they face and their recommendations for refining the FDIS to meet the needs of agricultural stakeholders in Tanzania. Indeed, the findings reveal that the stakeholders were ready to accept the FDIS design given the envisaged platform has the potential to solve many of their current challenges present in the complete farming cycle and could further motivate farmers and other stakeholders to target a more sustainable agriculture, to increase production and income, and be more respectful to the environment.

The most evident results of the analysis are the three additional services to the FDIS design proposed by the stakeholders, and the willingness of key stakeholders to adopt and use the envisaged FDIS platform. The additional services proposed for the FDIS design include transport and logistics, permit services from the authorities and information on warehouse services. We proposed the FDIS platform to be owned and managed by the government or under public/private partnership to achieve sustainability of the services (Mushi et al., 2022; Mushi, Burgi, & Di Marzo, 2023). Therefore, the Tanzanian government, through the MoA willingness and capability to adopt and manage the envisaged system, guarantee the availability of resources, particularly skilled human resources, ICT infrastructure and financial resources for maintaining and offering the services to the stakeholders. The current structure and available resources within the MoA are promising for further implementing and sustaining the envisaged digital platform. For instance, the MoA has an ICT section for developing, adopting, implementing, and supporting digital systems. Moreover, the MoA has a section specific for extension services to farmers and other stakeholders, which currently use the M-Kilimo application, which serves more than 6000 extension workers across the country. These pools of extension workers and ICT experts are essential for collecting and managing both the farmers and the farm data in the envisaged FDIS platform.

The gathering of comprehensive data related to farm business represents a major strength of the FDIS design for all stakeholders:

- Credit and insurance providers perceived the envisaged system as an opportunity to improve their services and increase access to the farmers at minimum risks.
- Farmers mentioned access to credit and insurance services as a catalyst to increased production through investing in modern agricultural tools and quality farm inputs. The study observed that most smallholder farmers currently use poor tools such as a hand hoe with intensive labor power and employ previous harvests as seeds due to a lack of capital for quality seeds, leading to low yield and income.
- Livestock farmers could hardly meet standards of their animal management such as use of local herbs for treatment as they cannot afford regular checkups and treatments from the veterinary service providers. Access to credit services should alleviate these difficulties.

The envisaged system has the potential to solve many of the identified challenges among farmers and make agriculture attractive to many unemployed youths in the country. Access to information and knowledge is also a key factor to increase the agriculture production

(Consolata, 2017; Mtega et al., 2014). However, the majority of farmers relied so far on their experience inherited from their parents, fellow farmers and general farming community, similar to other previous reported findings (Elly & Epafra Silayo, 2013; Ndimbwa et al., 2019). Poor access to extension and experts' advisory services and the lack of local and reliable information repository on agricultural matters affect the practices and experiences of farmers in such a way that many farming practices from farm preparations, crop or livestock management to harvesting and post harvesting activities are contrary to modern farming techniques, which result to low production and income. For instance, an agro-dealer mentioned that farmers buy and use inputs as recommended by a fellow farmer and previous experience but identify the inputs as substandard if they do not give the expected results. However, a few farmers using the experts and extension workers' services revealed to have increased their production. It is a fact that most farmers depend on seasonal rainfalls for farming but rely on their experience in forecasting the rainy season. This leads to many farmers claiming to lose their crops to severe droughts because of the weather becoming highly unpredictable due to the climate change. Farmers acknowledged that the envisaged FDIS platform could change their practices given they could without too much effort access to local agricultural content, experts' advice and extension services, as well as weather information forecasting from reliable sources.

This study found out that many smallholder farmers lack market information, letting middlemen use the information gap to gain benefits in the supply chains. Magesa et al. (2014) found that due to this misinformation rural farmers negotiate the prices of their agricultural products based on values provided by traders. Smallholder farmers are consequently often exploited by selling their products at lower prices than their true market value and are forced to sale as they lack market options, their agriculture produce being their primary source of income. Meanwhile, the processing industries rely on and buy agricultural produce from the middlemen as they lack direct access to buy from the farmers. The processing industries buy agriculture produce at a higher price (fixed by the middlemen), leading to high cost of production that end consumers have no choice but to pay. Farmers and processing industries acknowledged the potential of the FDIS design for eliminating the middlemen in the supply chain. Farmers mentioned that access to the market price information in the envisaged platform is crucial for bargaining and selling at better prices. Moreover, the ability to market agricultural produce and meet potential buyers across the country, including processing industries, will maximize their market options and sale at better prices hence increase their income. Processing industries added that the envisaged FDIS platform constitutes a bridge to buying agriculture produce directly from farmers at a lower price, which could also lower the price of the final products offered to the consumers. Furthermore, processing industries will be able to communicate with farmers on the quality and quantity of the products to match the market demands, making agriculture more dynamic and a resourceful enterprise. Table 9 presents a summary of common challenges raised by all agricultural stakeholders.

The stakeholders mentioned the challenges hindering their full potential in the agriculture sector. Some of the challenges raised were unique, as shown in Tables 1, 3, 5, and 7, while others were common to all stakeholders, as shown in Table 9. All stakeholders mentioned the lack of access to data, advisory services and information. Indeed, a comprehensive information system that collects and provides access to data and information services for all stakeholders is essential for sustainable agriculture. Other common challenges include stakeholder illiteracy and lack of awareness of different services such as agricultural credit, insurance, farming techniques and the use of digital services. This survey contributes to knowledge by understanding the problems of farmers and other stakeholders, in particular the common challenges to participation in sustainable agriculture. Finally, the survey contributes to the proposal of a comprehensive FDIS that resolves the unique and common challenges raised by stakeholders.

TABLE 9 A summary of common challenges raised by the stakeholders.

	Crop farmers	Livestock keepers	Agro-dealers	Extension workers	Insurance services providers	Credit services providers	Customers
Lack of access to credit and insurance services	√	√	×	N/A	N/A	N/A	N/A
Poor transport and logistics services	√	√	√	√	N/A	N/A	√
Poor access to data, advisory and information services	√	√	√	√	√	√	√
Market dependence on the intermediaries (middlemen)	√	√	×	N/A	×	×	√
Illiteracy and lack of awareness on different services from other stakeholders	√	√	√	√	√	√	×
Lack of storage and warehouse information services	√	×	√	N/A	N/A	N/A	√
Low quality farm inputs	√	√	√	N/A	N/A	N/A	N/A

Note: √ = Applicable, × = Not a challenge, N/A = Not Applicable.

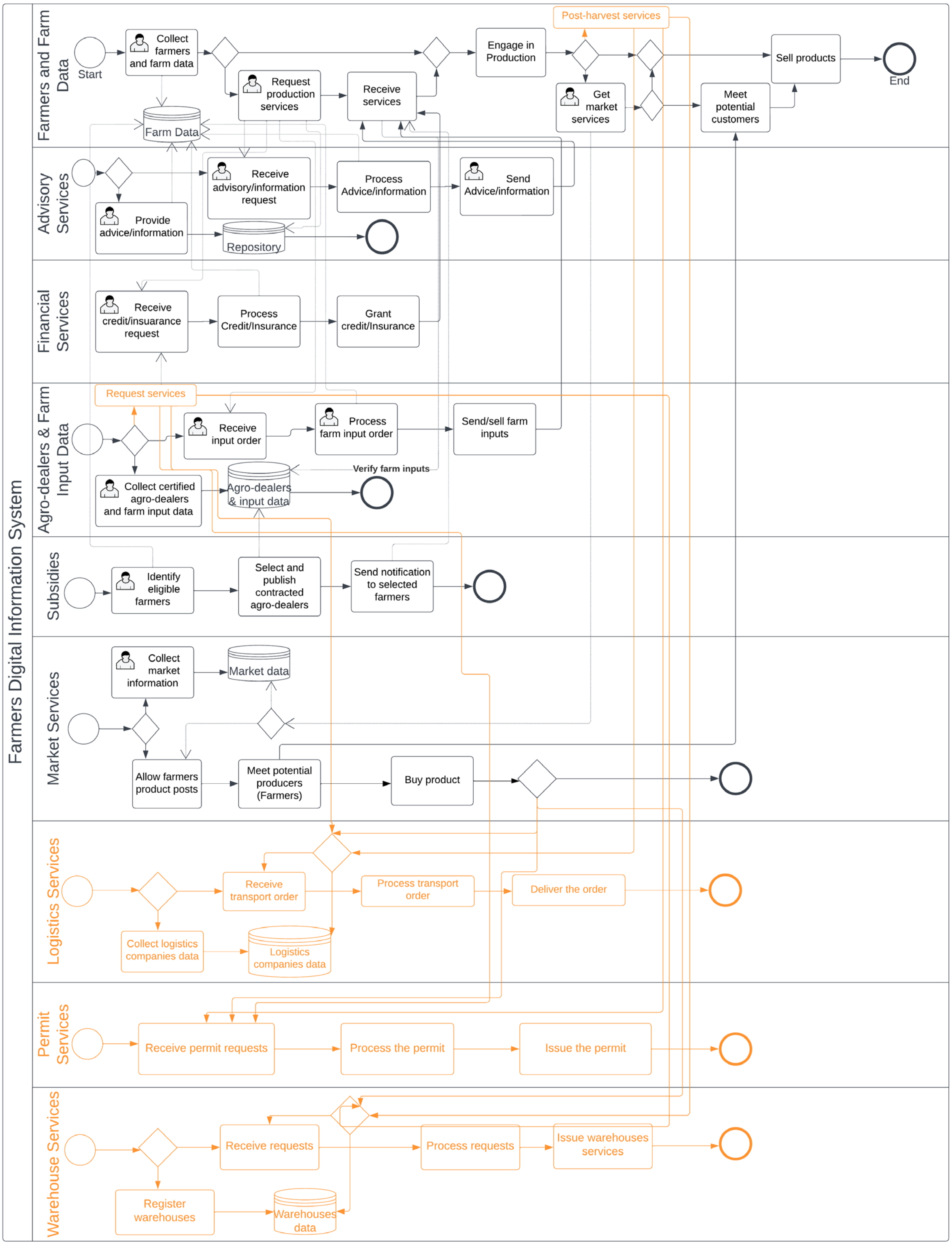

FIGURE 4 A refined FDIS BPMN diagram.

The challenges of implementing and using digital services in lower and middle-income countries, particularly in rural areas are still inevitable. The envisaged FDIS platform could face similar challenges to existing digital service to farmers offered by the MoA. These include illiteracy, digital illiteracy, poor infrastructure such as lack of power and Internet services in rural areas, and poor motivation to key stakeholders, particularly the extension workers. The study established that many smallholder farmers are old and could hardly adopt the new proposed technologies. Agriculture is perceived as a lower work class given most smallholder farmers lack primary education, which basically provide reading and writing skills.

However, even with primary level education the majority of people in Tanzania cannot read and write (Mmasa, 2016). Meanwhile, a study found that farmers with secondary and post-secondary education have the potential of using the right sources of information, can improve seeds, apply fertilizers, and benefit from credit services, and thus increase production and income (Kirui & Njiraini, 2019). Illiteracy is clearly a barrier to the use of digital services via devices such as smartphones, tablets, and computers. Despite the claims of increased mobile phone penetration in lower and middle-income countries, the use of smartphone in rural areas is still very low. The proposed FDIS platform as a web-based and mobile application service will thus not be accessible to many smallholder farmers who neither own digital devices nor have the ability to use them.

However, the envisaged digital platform aims at formalizing the agriculture sector and make it more attractive to many unemployed young people to engage in the agricultural production. This is supported by the Tanzanian government agriculture project via the MoA, called "Building A Better Tomorrow: Youth Initiative for Agribusiness (BBT-YIA)" for a period from 2022 to 2030. The initiative aims to create employment to growing unemployed population of youth who are challenged by negative perception towards agriculture, limited agricultural entrepreneurial skills, poor access to land, limited accessibility to financial services, markets; and modern agricultural labor saving and digital technologies to mention but a few (The United Republic of Tanzania, 2022). According to the MoA, 70% of labor force in Tanzania are youth, thus, their involvement in agriculture and digital technologies could eliminate challenges of illiteracy, access to and skills of use of advanced digital devices. Nonetheless, smallholder farmers' willingness to buy modern digital devices and acquire skills to use the envisaged platform is a major strength towards implementing the digital services.

6 | REFINED FDIS DESIGN

Opinions from key stakeholders in the agricultural sector suggested modifications to the FDIS functionality, making it necessary to develop a more refined artifact. Indeed, the stakeholders had good impression with the preliminary design and foresee its implications towards sustainable agriculture. However, they suggested more functionalities for the envisaged FDIS platform to achieve digitization of critical services in a complete farming cycle. In refining the FDIS, the stakeholders proposed to add the listed features to solve current problems that have not yet been addressed in the preliminary design.

- Logistics services
- Permit services from the authorities
- Warehouse services

Logistics services have emerged as an essential feature in the FDIS design, as proposed by agro-dealers, MoA, farmers, and customers. Agro-dealers are facing the challenge of transportation of inputs from the manufactures and importers to different regions in the country. Moreover, logistics services are key in the envisaged platform as farmers can order inputs for delivery. Agricultural produce from the farm to warehouses then to the market and from processing industries to consumers requires logistics services in place. Therefore, the stakeholders should be able to request the service from logistics companies through the FDIS. The MoA suggested that different permits from the authorities such as permits for harvest, transport, import and export of agriculture products be included in the FDIS design to improve efficiency and offer timely services to the stakeholders. Farmers proposed warehouse services in the envisaged FDIS platform to identify the availability of warehouse space and request for it based on their handheld digital devices or computers. The highlighted parts of the FDIS design in Figure 4 below present the additional functionalities as suggested by the stakeholders.

7 | CONCLUSION

Based on the study findings, it can be concluded that all stakeholders are in favor of the FDIS platform and were willing to participate to its design by proposing new features that improve the offer of services aiming at a more sustainable agriculture in the country. The envisaged digital platform has the potential of transforming and formalizing the agriculture system by bringing together key stakeholders, who will enable farmers to access the essential services composing a complete farming cycle. The government through the MoA is ready to adopt and manage the proposed FDIS platform with its structure and resources. This is promising for a successful implementation and sustainability of the digital services to be offered to all stakeholders. The challenges of using digital services such as digital illiteracy and poor infrastructure, particularly in rural areas, could be noticed. However, many smallholder farmers are willing to cooperate by acquiring digital devices and skills to use the envisaged platform. Moreover, the FDIS platform supports the Tanzanian government agriculture youth project "BBT-YIA" targeting unemployed young population who could be attracted by a more innovative agribusiness. Most of this population have acquired digital skills and have access to devices and Internet services, which could help them using the envisaged FDIS platform. This study, which involved stakeholders' views to determine the acceptability, usability, and problem solving of a digital intervention in the agriculture sector, paves the way for the future step of the actual implementation of the FDIS platform.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are openly available in Mendeley Data at https://data.mendeley.com/.

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Appendix E

Article V: A Farmers' Digital Information System (FDIS) for Sustainable Agriculture Among Smallholder Farmers in Tanzania.

information

MDPI

Article

A Farmers' Digital Information System (FDIS) for Sustainable Agriculture Among Smallholder Farmers in Tanzania

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Abstract: Digital technologies are promising tools for sustainable agriculture; however, the cutting-edge digital solutions in agriculture are impractical for smallholder farmers in developing countries. Smallholder farmers need access to credit and insurance services, quality farm inputs, advisory services, subsidies, and market services to be able participate in sustainable agriculture. This paper is part of an extensive study conducted using the design science research (DSR) methodology. As part of our previous research, we conducted a thorough survey of the various stakeholders in Tanzania to assess their needs. Thereafter, we designed a conceptual digital framework called Farmers' Digital Information System (FDIS), which provides all the necessary services to smallholder farmers and other stakeholders and addresses the identified needs. This paper presents a technical implementation of FDIS that aims to deliver essential services to smallholder farmers for sustainable agriculture within a comprehensive single mobile application. We used Android Studio Iguana and a Flutter framework to develop four service modules that include farmer and farm data, advisory services, and financial and marketing services as part of the FDIS platform. The system reflects the services offered in a real-world environment, as farmers can directly request advice from experts, apply for credit services from financial institutions, and market farm products to meet potential customers. It solves problems of access to farm advisory services and credit services for farm investment and helps farmers to find reliable markets for their products without going through intermediaries (middlemen). The completion of the FDIS development presented here will be followed by a test of the platform with real users for evaluation and improvement. Future research will focus on the scalability of FDIS for different regions, the embedding of more advanced technologies, and the adaptability of FDIS to different agricultural ecosystems. The FDIS solution has the potential to improve sustainable farming and empower smallholder farmers in Tanzania and beyond.

Keywords: information system; sustainable agriculture; smallholder farmers; system implementation; ICT in society; digital technologies; farmer digital information system (FDIS); Tanzania

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1. Introduction

Digital technologies are increasingly becoming an integral part of all social–economic activities surrounding human life. Indeed, technology innovations have tremendously altered the agriculture sector, promising sustainable agriculture, with increased productivity, income, and some environmental conservation [1,2]. These innovations include the use of big data and machine learning, artificial intelligence, robotics, the Internet of Things, and virtual and augmented reality, to name but a few, all leading to more efficient and climate-smart agricultural production [2–4]. However, these technological innovations are unevenly accessible to farmers around the world [5]. The cutting-edge technologies are mainly used by a minority of large-scale farmers, while many smallholder farmers continue to use old, inefficient tools and production methods. According to the UN Food and Agriculture Organization (FAO), large-scale farmers produce only around 30% of the world's food, while smallholder farmers account for 70% [5]. Therefore, it is worth noting that investing in new technologies for smallholder farmers could eradicate hunger and extreme poverty for the current and future anticipated population growth in the world.

Most smallholder farmers reside in rural and semi-urban areas in developing countries [6]. Smallholder farmers are facing various challenges that hinder them from practicing sustainable agriculture. Mushi et al. [7] established that a lack of access to agricultural knowledge and advisory services, poor access to financial resources (credit and insurance services), the presence of middlemen between farmers and the market, poor distribution of subsidies, the presence of counterfeit farm inputs, and poor policies are common challenges facing smallholder farmers in Tanzania and most other developing countries. The urgency of digital technologies as an essential component of production in all human socio-economic activities has influenced the need to solve the challenges of smallholder farmers. Indeed, many governments and non-governmental organizations have developed various digital solutions for smallholder farmers. For example, a recent study identified 94 digital agricultural solutions and startups in Tanzania, some of which are active while others are inactive [8]. To mention a few developing countries, government-initiated digital solutions in agriculture include the Online Fertilizer Recommendation System (OFRS) in Bangladesh, which provides location-specific fertilizer recommendations to improve the efficiency of farm input use, thereby reducing input costs and safeguarding the environment and consumers' health [9]; various digital solutions for different agricultural value chains by the Kenya Agricultural and Livestock Research Organization (KALRO) and a mobile service (m-service) for the dissemination of agrometeorological information in Kenya [10,11]; an e-Government platform serving the general agriculture community in India [12,13]; and many more.

In Tanzania, e-Government services in the agriculture sector have witnessed the implementation of M-Kilimo—a web-based and mobile application for farmers to access extension services and market information—a call center for farmers and general agriculture stakeholders, and a fertilizer subsidy distribution platform called the Digital Fertilizer Subsidy Distribution System (DFSDS), all in favor of smallholder farmers in the country [7]. However, all these digital solutions in developing countries only solve a particular problem, sometimes for specific agricultural value chains, which does little to solve the problems of smallholder farmers as part of a complete farming cycle. John [14] argued that most digital innovations for smallholder farmers use complex technology and lack testing, leading to incompatible systems. Moreover, most digital solutions do not integrate the components of sustainable agriculture, namely, the sustainability of the Information and Communication Technology (ICT) infrastructure and the resources that support the digital service, economic sustainability (increased income and productivity), and environmental sustainability.

This paper is part of a larger research study inspired by the theories of ICT for development (ICT4D), which posit that technology innovations must have an impact on people's lives [15,16]. Therefore, we intended to design and develop digital solutions that work well for smallholder farmers in developing countries, without copying and pasting the theories and technologies used by large-scale farmers, mainly in developed countries. As a part of a more in-depth study, this paper contributes to the body of knowledge on the implementation of *Farmers' Digital Information System (FDIS)*, a digital platform that aims to provide all essential agricultural services as part of a complete farming cycle and under one roof. The previous parts of the study focused on the design phase, which analyzed the challenges and needs of agricultural stakeholders in Tanzania—a low-income country [17,18]. Chandra and Collis [19] found that the challenges of smallholder farmers in developing countries are more similar to each other, so the FDIS concept could be adopted with minimal contextual adjustments to fit the agricultural system of any other developing country.

As said above, our previous research reviewed digital technologies for sustainable agriculture in Tanzania [5]. We then thoroughly investigated the needs of smallholder farmers and other stakeholders in Tanzania [7,17] in order to establish a proposal of the design of FDIS, a comprehensive digital framework regrouping all services useful for farmers [18]. To validate our proposal and to bridge the gap towards a concrete digital solution, we discuss in this paper how we implemented a few FDIS services and provided them in an integrated way to the farmers through a single mobile phone or web application. More specifically, the main contribution of this paper is the implementation and illustration of three modules (i.e., data on farm and farmers, financial, advisory, and market services) as part of the complete FDIS platform. Section 2 presents the methodology and materials required to implement the platform. Section 3 explains the results of the implementation, including the designs of the implemented part of the system and the interface and functions of the modules. Section 4 discusses and illustrates the impact of the implemented part of the system in the real world and the impact on the development of the agricultural sector. Moreover, Section 4 discusses various issues regarding the actual implementation of FDIS, while Section 5 concludes the paper with key notes on the findings and future areas of research.

2. Materials and Methods

We adopted a design science research (DSR) method, which strives to develop high-quality digital solutions that interact with the problem's context and result in effective and efficient information systems [20]. DSR is a solution-oriented methodology that has been established as an effective method that goes beyond descriptive–explanatory research and takes steps to solve problems. DSR is gaining ground in the field of information systems, information technologies, and related disciplines due to its ability to solve a social–technical problem by designing an artefact, a model, and a procedure that fit well into the context of a specific environment. However, behavioral science research (BSR) and other conventional methodologies dominate research in the areas mentioned due to the low awareness of DSR among scholars [21]. This study is guided by the theories of ICT4D—Information Technology for Development—which emphasizes that "Key elements in the ongoing work towards sustainable development will be the ability of stakeholders in development initiatives to collaboratively and effectively design, implement and evaluate innovations that will be adopted and utilized within specific development contexts and environments" [21]. DSR is the preferred methodology for ICT4D projects because of its ability to develop and implement digital solutions that meet the evolving needs of stakeholders. Indeed, DSR uses qualitative and quantitative tools to collect and analyze data with a view to developing a sustainable digital artefact and models for solving socio-technical problems in society [15,21].

Adopting and customizing the DSR process by Peffers et al. [22], we developed eight steps for designing and implementing the FDIS platform. The first step was to identify the problems facing smallholder farmers that need digital technology intervention. The problems were identified through a literature review, which identified the lack of investment capital and financial services, the poor subsidy distribution system, and the lack of access to quality farm inputs, advisory services, and a reliable market for farm products as common challenges for smallholder farmers [5]. The second stage consisted of gathering the system requirements by defining the objectives that would meet the challenges identified. This was followed by a third stage of the preliminary design of the artifact based on the requirements identified in the previous stage [23]. The fourth stage was to conduct a survey of key stakeholders to orient users to the preliminary design of the artifact and to collect their opinions on the problem solution. We conducted a user survey to gain user input early in the design phase, as user opinions are important for digital solutions projects [24]. In the fifth stage, we developed a concrete design based on the opinions and needs of stakeholders that were missing from the preliminary artifact that was designed. The sixth stage was the pilot implementation of the refined FDIS design, i.e., the actual development of the system.

We introduced agile methodologies in the implementation phase (in the dotted box in the phase sixth and seven) in order to gradually build the FDIS system from scratch and rapidly adopt contributions for system improvement in an iterative approach. Agile methodologies, unlike others, allow for a gradual implementation of the system, the adoption of changes for necessary improvement, and the involvement of stakeholders at all levels of the system's development [25,26]. This stage brings together designers, developers, and users, who contribute to the continuous improvement of the system. The seventh stage was the evaluation of the implemented part of the FDIS platform. This involved monitoring the effectiveness and efficiency of FDIS, while allowing users to provide feedback, thereby returning to the design stage. The eighth stage was the communication and documentation of the system through scientific and professional publications. This stage was reached at every stage of the DSR methodology used in this project. Figure 1 illustrates the eight stages of the DSR methodology:, from the identification of the problem and requirements to a preliminary proposal of an artefact design (in our case, a preliminary FDIS proposal), to a user survey that helped us revisit and refine our FDIS proposal, to the actual development and evaluation of the FDIS platform, and to finally communicating the results. This process is iterative, and at any point in time, we may go back and revisit previous decisions or embark in a new DSR research cycle. Figure 1 specifically highlights the sixth stage (in yellow) described in this paper, which concerns the implementation and evaluation of the FDIS platform.

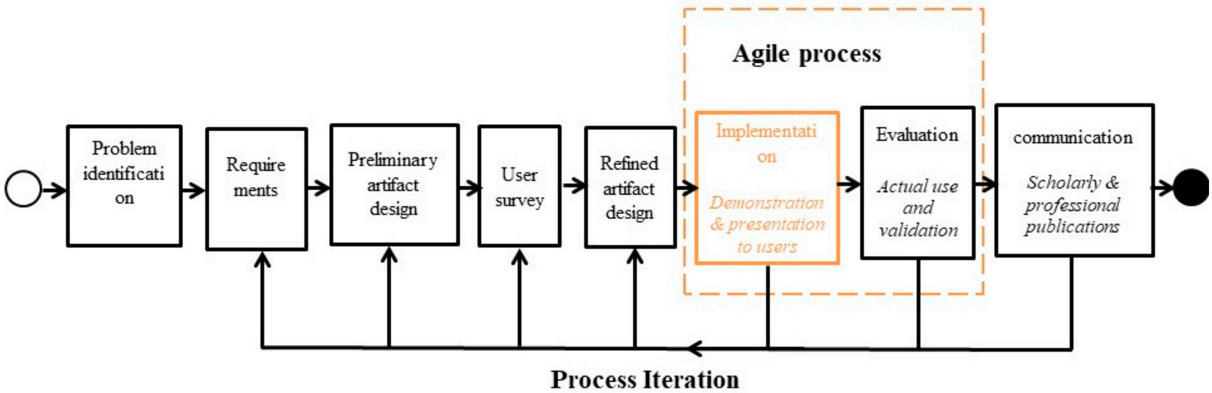

Figure 1. The DSR method used in this project.

3. FDIS Implementation—Design, Development, and Deployment

The section presents the technical design, development, and deployment of the system for demonstration purposes, showing how the system meets the needs of users with a view to the adoption of sustainable agriculture. We present here the software components of FDIS and how they interact with each other, as well as the deployment of FDIS for access to the various users. Concerning the actual implementation, we used the Android platform to develop farm and farmer data modules, financial modules, and advisory and market modules as part of the FDIS services. The researchers used Android Studio Iguana and a Flutter framework to develop four service modules that included farmer and farm data, advisory services, credit services, and marketing services as separate services [27]. The services developed can be accessed on Android and iOS devices and via web applications.

3.1. FDIS Services Components

Figure 2 below shows a Unified Modeling Language (UML) component diagram that corresponds to the complete FDIS designed services shown in the Business Process Modeling and Notation (BPMN) by Mushi et al. [18]. On the left of the figure, the farmers services component can be seen, which is itself composed of several sub-components (farmer database, get advisory service, get financial service, get agro-dealers services, get subsidies service, manage harvest, and manage market). These components communicate with the components (shown in the middle of the figure) providing those services to the farmers (advisory, financial, agro-dealers, subsidies, logistics, and market services). Those services, in turn, need access to additional services shown by the components on the right of the figure, such as permit or warehouse services. The four service modules highlighted in color in Figure 2 below correspond to the components implemented for the demonstration. The UML component diagram shows the deployment of FDIS platform and service interactions solving critical challenges of the farmers and other stakeholders towards sustainable agriculture.

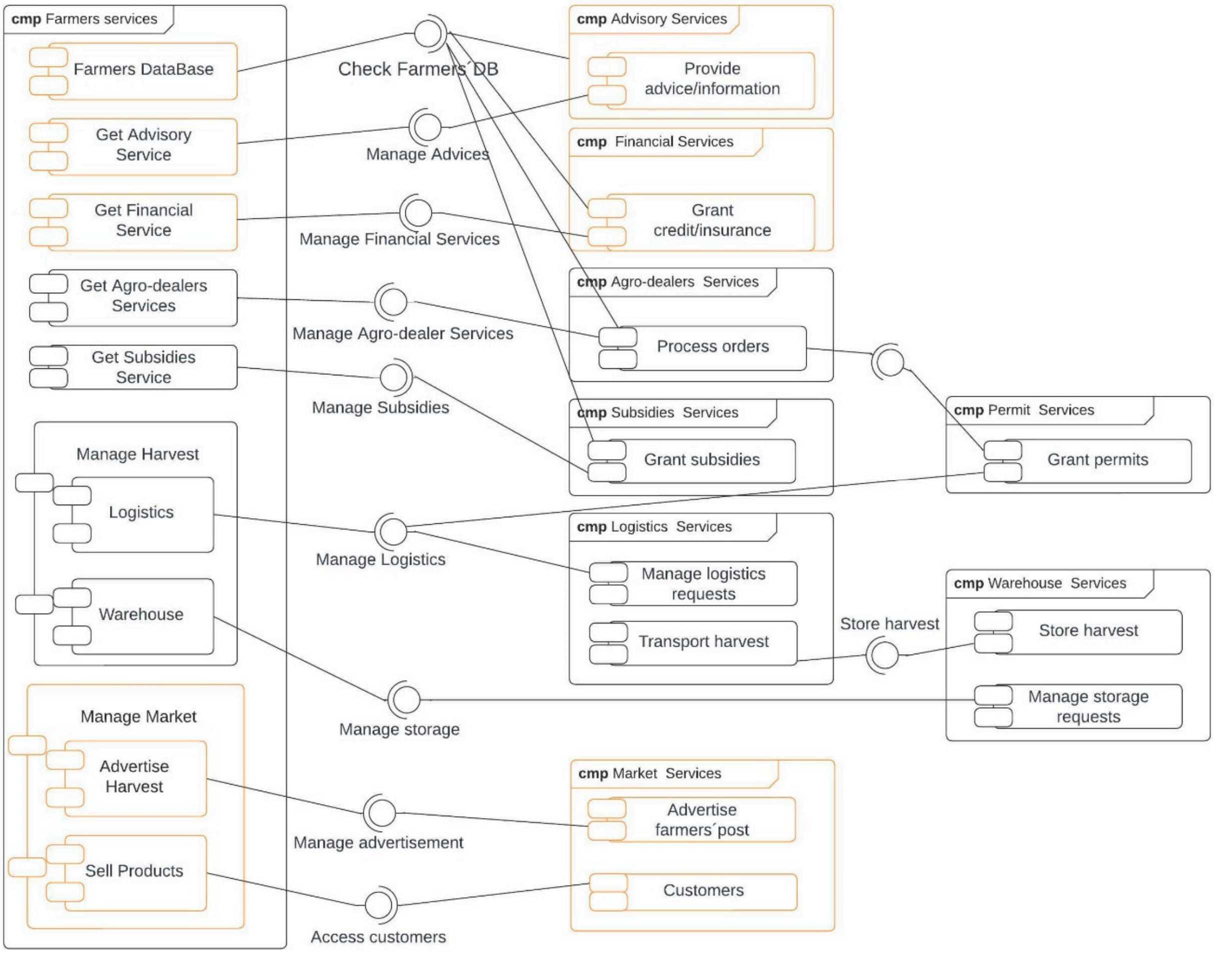

Figure 2. FDIS UML component diagram.

More precisely, FDIS comprises several essential services that bring together all key stakeholders in the agriculture sector, including the government. The fundamental component of FDIS is the "farmers services" component (left side of Figure 2). This component hosts several sub-components, including the farmers database, that other stakeholders can request data from during the service delivery. The farmers database presents comprehensive data regarding the farms and farmers. Other sub-components of the farmer services include access to advisory, financial, agro-dealers, and subsidies services, as well as two components for managing the harvest and the market (advertising and selling products). FDIS also comprises components for services providers (in the middle of Figure 2), such as financial (credit and insurance services), advisory, agro-dealers, and subsidies. The agro-dealer service is further linked with the permit service. These services require data from the farmers for quality and timely service delivery. Additional components concern services in relation to logistics and the market. The harvest and logistics services are further linked with the warehouse services for storing the harvest. Therefore, farmers can request and receive services from all the stakeholders through the system that can be accessed by all mobile devices (Android and iOS) and also from the website. Subsidies are government-initiated services in Tanzania; thus, the responsible department uses farmer data (after registration) to deliver the service (see Figure 2). For the market service, farmers are expected to post their farm products so that interested customers can contact the farmer for business.

3.2. FDIS Development

The developers used Android studio Jellyfish 2023.3.1 patch 1 (which includes version AI-233.14808.21.2331.11842104, built on 15 May 2024). The development of FDIS was supported by Flutter plugins with dependency features such as a curved navigation bar, firebase core, firebase auth, cloud firestone, random string, shared preferences, image picker, and firebase storage.

Moreover, we used the Google's Firebase (version 13.15.1) mobile application development platform for the project as it offers a comprehensive toolset that includes services like analytics, authentication, databases, file storage, and push messaging. Firebase is a cloud-based service that interacts directly with the client Software Development Kit (SDK) provided by Firebase, eliminating the need for developers to build and maintain backend infrastructure. The platform caters to various app development needs across different platforms such as iOS, Android, the web, Flutter, Unity and C++.

3.3. FDIS Deployment

The client–server model was adopted, whereby users can access services via personal computers and mobile devices. Users have to register either through the application or the website to obtain access to the services stored in the web server. The main application (back-end) runs on a dedicated computer (web server). Access to the application occurs either through a web interface (front-end) via a personal computer or through a mobile application to be downloaded on a mobile device. The web server enables access to the FDIS platform from a computer or mobile device. The client–server model approach is crucial to enabling access for multiple devices to the application while synchronizing media libraries between devices. We used the Firebase database, a mobile application development platform from Google that supports a variety of application development needs, including the major mobile device operating systems (iOS and Android) and web services.

4. Discussion

The FDIS platform is a promising tool for sustainable agriculture among smallholder farmers, as it provides essential services in a complete farming cycle. Moreover, the platform could contribute to smallholder farmers' adoption of climate-smart agriculture (CSA), namely, increased productivity, support resilience, and climate mitigation [4,28]. FDIS is a comprehensive digital platform designed to offer eight essential services as it brings agricultural stakeholders together. These services include financial, advice from experts, agro-dealers and farm inputs, warehouse and logistics services, administrative services from government agencies, subsidies, and market services [17]. The basis of the FDIS platform is the management and sharing of comprehensive farm and farmer data. The three services implemented provide farmers with access to financial, advisory, and market services via digital devices such as smartphones, tablets, and computers. We focused the discussions on the impact of digitized services and the contribution to sustainable agriculture for most smallholder farmers in developing countries. In what follows, we present an illustration of the three services implemented for demonstration and presentation purposes.

4.1. Illustration of FDIS Applications

4.1.1. Financial Services

According to Kirui et al., [29], Simbakalia [30], and Kimaro [31], farmers lack investment capital because they rely on their personal assets to invest in production. A survey conducted under this project revealed that only a few farmers approach financial institutions for services in Tanzania. Meanwhile, farmers experience long application procedures and denial or have insufficient credit needed for production. On the other hand, the financial institutions consider farmers as high-risk customers and impose strict conditions for access to credit services [23]. Therefore, the majority of smallholder farmers are unable to invest in modern farming and animal-keeping, resulting in poor production, low income, and environmentally unfriendly agricultural practices. The poor relationship between smallholder farmers and financial institutions is due to a lack of data. There are no reliable data that introduce farmers to other stakeholders for a service. For example, for a bank to verify the information provided by farmers when applying for a loan, it must call on its agent to physically visit the farm, interview neighbors and local authorities, etc. Farmers have complained about the time it takes to obtain a loan, and most of them obtain the loan when the time needed for farming has elapsed. As a result, they use the loan for other unplanned purposes, which prevents them from repaying the loan [23]. This vicious cycle of mistrust and lack of cooperation is hampering the growth of the agricultural sector and efforts to eradicate extreme poverty and hunger in the global community.

The digitization of the financial service within the FDIS platform was designed to solve the problem of data management for smallholder farmers. The platform accurately collects farm and farmer data to share with other stakeholders as a service. FDIS was designed to collect all essential data needed by different stakeholders, including financial institutions. These dataset categories include personal information, communication information, location details, farm and field data, financial instruments and credit information, insurance, production data, and business information [17]. Data collection in the platform involves different actors and levels of verification for quality assurance. FDIS applies data shielding during data sharing for services to adhere to the privacy and security of data. Therefore, not all farmer data will be openly available when exchanging services with stakeholders. Pre-defined conditions for data access by each stakeholder must be defined to ensure that each stakeholder has access to sufficient data to enable the provision of services to farmers. For instance, financial institutions could use FDIS to request and access farmer data, like the manual forms used to collect data from farmers when applying for services.

FDIS could increase efficiency and collaboration between smallholder farmers and financial institutions. Smallholder farmers could apply credit services by simply sharing the information needed by financial institutions. Simplified verification of farmer information by financial institutions could trigger timely credit services, grant sufficient loans needed for production, and improve the conditions of access to financial services for smallholder farmers. The survey carried out as part of this project revealed that one of the reasons for the poor relations between smallholder farmers and financial institutions is the lack of data on farms and farmers. FDIS can promptly provide financial institutions with comprehensive information on farms and farmers. Information such as the business plan, production history, and farm financial statements are essential for assessing the financial stability of the farm and for risk management. This information is critical to reducing the risks of loans granted by financial institutions as well as to offering other credit services effectively.

4.1.2. Advisory Services

The digitization of information and advisory services to smallholder farmers could solve many economic and environmental challenges in developing countries and in Tanzania in particular. It should be noted that most smallholder farmers do not have access to modern agricultural farming knowledge or expert advisory services, so they rely on their own knowledge and that inherited from the farming community [7]. A recent study on the extended knowledge system in Tanzania revealed a disconnect at multiple levels, thus hindering sustainable agriculture among smallholder farmers [32]. This leads to poor farming practices, such as poor selection of breeds and the use of sub-standard farm inputs, posing a serious threat to the quality and quantity of production, the health of farmers and consumers, and the environment [33–35]. A survey undertaken in this project revealed that most farmers are not trained to adopt basic farming and animal-keeping practices and technology. For these reasons, the Tanzanian government employs extension workers—agriculture experts employed to transfer agricultural knowledge and technology from various sources to farmers. These extension workers work closely with farmers at a ward level. However, this method of transferring knowledge is ineffective because of staff shortages and the difficulty of reaching large numbers of farmers in remote areas [23]. However, some other parts of the country are using radio and short messages (SMS) to disseminate and access extension information, with radio being the preferred channel of sharing information to smallholder farmers [36]. Figure 3 presents the front-end (or interface) implementation of advisory services, enabling farmers to access and request information on various farming activities such as seeds, farm machinery, crops, crop diseases, labor sources, pests and diseases, farm inputs, etc. It is the interface that is presented to the farmers to obtain access to the services. It corresponds to the FDIS get advisory service components highlighted in color on the left side of Figure 2.

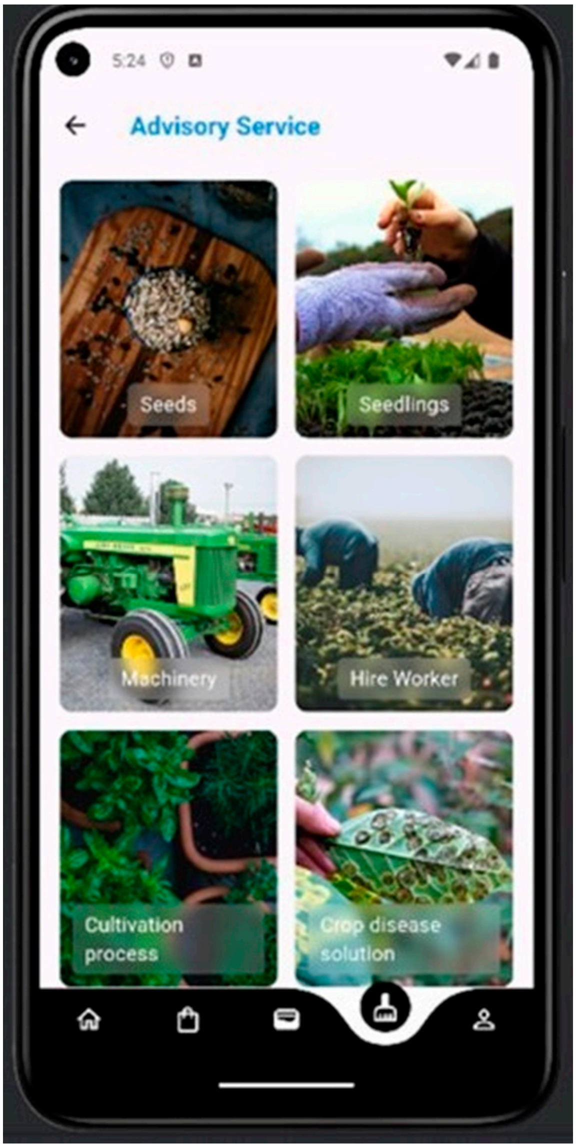

Figure 3. Advisory services—a part of the FDIS implementation (farmers' access).

Figure 3 shows six advisory services available for the user. The user can select a service category for more specific needs, for example, a specific type of crop disease under the "crop disease solution" or a specific crop cultivation process under the "crop cultivation". We implemented these few advice categories for demonstration purposes, but other advice categories may be introduced as part of the actual implementation of the FDIS platform.

The FDIS platform's advisory services are designed to mitigate the challenges identified in terms of sustainable agriculture. It involves the registration of agricultural experts and farmers [17]. The experts will be registered in the system and will be able to respond to the various information or advice needs of farmers. This solves the problem of farmers' dependence on their knowledge in all farming activities, including the application of farm inputs. The ability of farmers to request and receive information and advisory services on various farming activities is essential to increasing productivity and income and to avoid inferior inputs that could be harmful to the health of farmers, consumers, and the environment. The systematic adoption of these practices and other FDIS services would ensure that smallholder farmers are committed to sustainable agriculture.

4.1.3. Market Services

Smallholder farmers could increase their income and profitability if they found a reliable market for their products without intermediaries in the supply chain [17]. Intermediaries (middlemen) play the role of information brokers. They identify areas where farmers are selling their products at low prices because they lack market information, usually before or shortly after harvest. Intermediaries set the price for farmers and buy without government control, selling at higher prices to processors and consumers [37]. This practice demotivates farmers and diminishes their ability to increase their investment in agricultural production [38]. We conducted a survey of farmers, processors, and consumers, among other stakeholders. The results revealed that farmers mainly sell to intermediaries at very low price, while processors and consumers buy from intermediaries at higher prices [23]. Processors and consumers felt that buying directly from farmers could not only increase their profitability but also enable them to buy agricultural products at a fair price, unlike with intermediaries. However, the lack of information and communication between the agricultural processing industries, consumers, and farmers is a challenge that is exploited by intermediaries. To avoid the frustrations of the market and the inability to grow, farmers cut back on production, as they primarily aim for subsistence rather than agribusiness, leading to a shortage of food and raw materials produced by agriculture.

Figure 4 below shows the interface implementation of market services that enable farmers to display their products and meet potential customers. It is the interface that is presented to farmers to obtain access to the market services. It corresponds to the FDIS manage market component highlighted in color on the left side of Figure 2. This interface shows three cereal crops as a demonstration of the FDIS platform: rice/paddy (in the illustration), wheat, and maize.

Customers can navigate to any of the cereal crops they wish to buy directly from farmers. After selecting the crop, customers can browse a list of products posted by farmers, identifying price tags, location, farmer contact details, and quality and quantity of produce. This information is critical to enable customers to decide whether or not to buy the products. We implemented the three crops only for demonstration purposes, but other crops may be accessible when the platform is actually implemented.

FDIS is designed to link all the key stakeholders in agriculture, including farmers, processing industries, and consumers. This link could radically change the supply chain for agricultural products by eliminating intermediaries. In addition to access to market information, farmers would be able to market their products and meet potential customers directly, particularly from the processing industries and consumers. The survey revealed that on the one hand, farmers would be able to sell their products at a fair price and earn a deserved income if the platform enabled them to access market information and reach a wider market; on the other hand, the processing industries believe that buying raw materials directly from farmers reduces production costs and the cost of processed food for end consumers [23]. As a result, farmers can increase their investment in agriculture and productivity, which promotes sustainable agriculture and the development of the majority of people employed in the sector.

Figure 4. Market service—another part of the FDIS implementation (farmers' access).

4.2. Towards the Effective Implementation of FDIS

Although FDIS has the potential to make the agriculture sector more dynamic and sustainable, a number of issues need to be considered for its effective implementation. FDIS is a comprehensive digital platform that requires the efforts of various key agricultural stakeholders, including experts from different disciplines, governmental, and non-governmental organizations. Smidt and Jokonya [39] ascertained that government and institutional support is critical to bringing together agricultural stakeholders and to develop a localized developmental implementation framework for supporting the adoption of digital solutions to support smallholder farmers. The FDIS platform is a data-driven digital solution to the challenges faced by smallholder farmers in developing countries. Farmer and farm data are the key components of the FDIS platform, and farmers, service providers, and other stakeholder can share these data when requesting and providing services. This raises issues of data quality (completeness, accuracy, timeliness, and precision of data), data ownership and sovereignty, and legal issues relating to data protection. Implementing the FDIS platform will require training stakeholders on the importance of data quality and training staff responsible for collecting and regularly updating the data. Moreover, FDIS could use the Application Programming Interface (API) to verify stakeholder data from existing systems such as the National Personal Identification System. More advanced technology, such as sensors, unmanned ground vehicles, and unmanned aerial vehicles, could be used to collect quality data; however, such technology requires a considerable initial cost [13].

Data ownership and sovereignty have become a critical topic of discussion when implementing data management systems. The debate about data ownership between farmers, companies, and the organizations that manage the digital platform infrastructure is still ongoing. Many existing data ownership models show that agricultural technology providers are taking control of data and reusing it for their own benefit [40]. Although new policies transfer ownership of data to farmers, the problem of data dispersal remains; data can be copied, transferred, and migrated and can exist in different locations and under different ownership [6]. Nonetheless, good practice of data ownership can be adopted when developing policies governing the implementation of data-driven systems. For example, an open data charter would allow farmers to share all or part of their farm data with service providers, such as fertilizer companies, while giving data owners (farmers) the right to delete their data and opt out of the platform, thereby exercising data ownership and protection [3,40]. Many governments of developing countries are developing policies and legislation on data protection and data sovereignty. For instance, Tanzania has drafted its personal data protection legislation to control the collection, storage, and sharing of data [41]. In the meantime, common legislation can be used to implement the FDIS platform, according to which the collection, storage, and sharing of personal data require the consent of farmers, who must be aware of the purpose for the data collection and the list of companies or organizations with which the data will be shared [42].

FDIS is a complete digital artefact designed to digitize the national agricultural system. Therefore, the effective implementation of FDIS requires enormous resources, namely, infrastructure, trained staff, and financial resources. The partnership between the government and the private sector could benefit from the use of existing infrastructure and resources for the adoption of the FDIS platform. For example, the Tanzania Ministry of Agriculture (MoA) has invested in digital technology to serve farmers and other players in the country's agricultural sector. ICT-based services implemented by the MoA include M-Kilimo, which is a web and mobile application for farmers to access extension services and market information, a call center for farmers and agricultural stakeholders in general, and a fertilizer subsidy distribution platform called the Digital Fertilizer Subsidy Distribution System (DFSDS), all for the benefit of smallholder farmers in the country [7]. FDIS can inherit existing infrastructure, human resources, and data from farmers and other stakeholders without starting from scratch. Moreover, other government employees, particularly agricultural extension officers (employed throughout the country) could play a key role in the collection and regular updating of farmer data in the platform. All of these elements could significantly reduce the cost of implementing FDIS but could also ensure the quality of the data and services and guarantee the sustainability of the infrastructure and resources that support the platform.

5. Conclusions

Service providers such as financial institutions offering credit and insurance services, agriculture experts, government agencies, agro-dealers, processing industries, and others lack reliable and comprehensive information on farms and farmers. It is difficult to provide services such as credit and insurance, advice, subsidies, farm inputs, and market services to farmers without a reliable source of information on the farms and farmers. As part of an ongoing research project, we designed and implemented a digital framework called FDIS that brings all agricultural services together. FDIS facilitates key stakeholders' access to comprehensive data on farms and farmers for the provision of those services. Our contributions are three-fold: (1) from the academic point of view, we provide a proposal, called FDIS, for a novel data management system that integrates farmer data as well as farmer services within a comprehensive single system that gathers the various stakeholders [17]; (2) from a technical and practical aspect, we designed and described the various software components and their interactions, as well as an interface design for farmers, all supporting the concrete implementation of FDIS; (3) from a societal point a view, we provide a proposal for a system aiming at empowering smallholder farmers [7,18].

This paper highlights the second point above, i.e., the design and implementation of the FDIS digital platform and its provision to farmers in the form of a mobile application. The management and sharing of farm and farmer data play a key role in this platform. The FDIS platform has the potential to make the agriculture sector more dynamic and increase its contribution to sustainable development in low- and middle-income countries.

However, the implementation of FDIS requires consideration of issues that are essential for the sustainability of the platform and the agricultural services offered to farmers. Indeed, farm data management has become a topic of interest in recent years, raising new challenges such as data ownership and sovereignty, data quality, and legal issues relating to data protection. In addition, the implementation of FDIS could face the challenges of digital illiteracy among farmers and other stakeholders, network coverage, particularly in rural areas, and the lack of young people in agriculture. Therefore, we are calling on local governments, non-governmental organizations, and international partners to work together to alleviate the challenges of harnessing the full potential of digital technologies in agriculture. Areas for collaboration include digital literacy training, the development of good policies, infrastructure development, particularly in rural areas, and encouraging young people to invest in agriculture.

This paper is a steppingstone for future research and development of the platform. FDIS has been developed in the context of the Tanzanian agricultural system, which is similar to that of many other developing countries. Therefore, future research could focus on examining the scalability of the FDIS platform in the context of other countries. Furthermore, we recommend that future studies explore technological advances that could further enhance the FDIS platform. For instance, by looking at AI and the IoT, the FDIS platform could improve precision agriculture. This also provides an opportunity to examine the long-term impacts on smallholder productivity, income, and environmental sustainability, which is valuable for further development.

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