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Digitalization of precision fertilization in East Africa: adoption, benefits and losses

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Introduction: The rapid digitalization of agriculture in East Africa has spurred the adoption of precision fertilization tools, which optimize nutrient application and enhance crop yields. However, the extent of digital technology adoption, its benefits, and the challenges smallholder farmers face in the region remain unclear.

Methods: A systematic review adhering to PRISMA guidelines assessed the adoption of digital technologies for precision fertilization in East Africa. A comprehensive search of English-language studies published between 2010 and 2024 resulted in fifteen studies that met the inclusion criteria.

Results: The review highlights digital solutions that assist smallholder farmers in sustainable resource management, including mobile applications, ICT tools, Variable Rate Application (VRA), and AI/ML technologies. Reported benefits include improved crop productivity, increased economic efficiency, and enhanced environmental sustainability. However, issues with data accuracy, limited access to technology, affordability constraints, and low digital literacy hinder widespread adoption.

Discussion: The findings emphasize the need for further research and the development of tailored strategies to enhance digital agricultural practices in East Africa. Addressing socioeconomic and infrastructure challenges is crucial to ensuring equitable access and maximizing the effectiveness of digital precision fertilization tools. This review provides valuable insights to support stakeholders in developing sustainable, data-driven agricultural frameworks to improve regional food security.

KEYWORDS

precision fertilization, digitalization, precision agriculture, East Africa, variable rate application (VRA)

1 Introduction

Precision agriculture is an innovative approach to farming that utilizes advanced technology to optimize crop yields while minimizing resource usage and environmental impact (Finger et al., 2019). In East Africa, where agriculture is a major contributor to the economy and a significant source of livelihood for millions of people, the adoption of precision agriculture has the potential to revolutionize the sector (Mapiye et al., 2021). Fertilization is one of the most important aspects of crop production, and it is critical to achieve optimal yields and improve food security. However, fertilizer application is a complex process that requires careful management to ensure nutrients are applied efficiently and effectively (Ju and Christie, 2011). The use of fertilizers can also have significant environmental and economic consequences, which need to be considered. Environmental impacts of fertilizer usage include soil and water pollution, greenhouse gas emissions, and biodiversity loss (Savci, 2012). Excessive use of nitrogen fertilizers can lead to nitrate leaching, which can contaminate groundwater and cause harmful algal blooms in lakes and rivers (Bashir et al., 2013). Phosphorus runoff from fertilizers can contribute to eutrophication, leading to oxygen depletion and fish kills (Kleinman et al., 2011). The economic effects of fertilizer use are also significant. The cost of fertilizers is a major expense for farmers, particularly sub-Saharan Africa (including and mostly East African countries), where studies show that fertilizer prices are considerably higher than other developing countries. The price volatility of fertilizers can impact agricultural production costs and food prices (Chianu et al., 2012). This complexity of fertilizer application explains the need for precision fertilization, which is gaining popularity to deliver the right amount of nutrients to crops at the right time, leading to increased yields and better-quality produce (Quebrajo et al., 2015).

In recent years, there has been a growing interest in utilizing mobile apps, information and communication technologies (ICTs), variable-rate applications (VRA), artificial intelligence (AI), and machine learning (ML) to optimize fertilizer use and enhance crop yields in East Africa. Applying these technologies for site-specific fertilizer application offers a practical solution to the challenges facing both large enterprises and smallholder farmers in the region, including soil degradation, nutrient depletion, and water scarcity. While these technologies have the potential to revolutionize fertilizer application and improve agricultural productivity in East Africa, their adoption comes with challenges and risks, necessitating careful consideration to ensure sustainable and equitable implementation.

Adopting digital technologies for precision fertilization aligns with the broader goal of establishing sustainable food production systems in East Africa. By minimizing input waste, improving soil health, and maximizing yields, these technologies offer scalable solutions to critical sustainability challenges.

Despite global advancements in precision agriculture, the adoption of digital technologies in East African agriculture remains underexplored, presenting a critical research gap. This study seeks to address this gap by systematically reviewing the adoption, benefits, and limitations of precision fertilization technologies in the region. Our primary objective is to offer a comprehensive understanding of current adoption trends and to identify key challenges and opportunities for future research.

This review aims to provide a comprehensive analysis of these technologies' current state and impact on fertilization in East Africa, as well as to identify opportunities and challenges for their adoption in the region.

2 Methodology

The Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) method was employed to collect and sort out different research materials to prepare this review article. The PRISMA method is a systematic approach that enables the researcher to identify, screen, and select relevant studies for inclusion in the review (Page et al., 2021). The review process involved a comprehensive search in different online databases such as Google Scholar, Science Direct, and Scopus for studies that examined the adoption, benefits, and losses of digitalization of precision fertilization in East Africa. The search was conducted in June 2024 using a combination of the following keywords; "digitalization," "precision fertilization," "East Africa," "adoption," "benefits," and "losses" and was limited to articles published between 2010 and 2024. The search results were then screened based on predefined inclusion and exclusion criteria, and the full text of the selected studies was reviewed to extract relevant data. The inclusion criteria used to select studies were as follows:

i Relevance to precision fertilization using digital technologies: Studies had to be directly related to the central topic of precision fertilization and the use of modern digital technologies such as mobile applications, information and communication technologies (ICTs), variable rate application (VRA), artificial intelligence (AI), and machine learning (ML) in East Africa. This included research that specifically focused on or was conducted within East African countries and studies on precision fertilization technologies with applications or implications for the East African context. The role of digitalization in enhancing precision agriculture practices and overcoming agricultural challenges in the region was emphasized (e.g., Finger et al., 2019; Krell et al., 2021).

ii Reporting of benefits or barriers to adoption: Studies need to report either the benefits or losses associated with precision fertilization technology adoption. Benefits might include improved crop productivity, environmental sustainability, and economic efficiency, while barriers could include technical, socio-economic, and infrastructural limitations specific to East Africa (Mapiye et al., 2021; Dara et al., 2022). The technologies and methods examined in each study were reviewed to identify those most relevant to East African agricultural practices, such as mobile applications tailored for smallholder farmers or AI systems adapted to limited connectivity environments.

Thirty-eight articles were found relevant to the study and selected. The limited number of studies included in this review reflects the emerging nature of digital precision agriculture in East Africa. This scarcity not only indicates a research gap but also highlights an opportunity to explore and establish best practices for technology adoption in this context.

Data extraction was done using a standardized data extraction form, and the quality of the studies was assessed using a predefined set of criteria, as presented in Figure 1. Finally, the findings from the selected studies were synthesized and summarized to provide a comprehensive overview of the topic.

3 Results

3.1 Overview of findings by technology type

In our systematic literature review, we identified four primary constructs in the application of digital technologies for precision

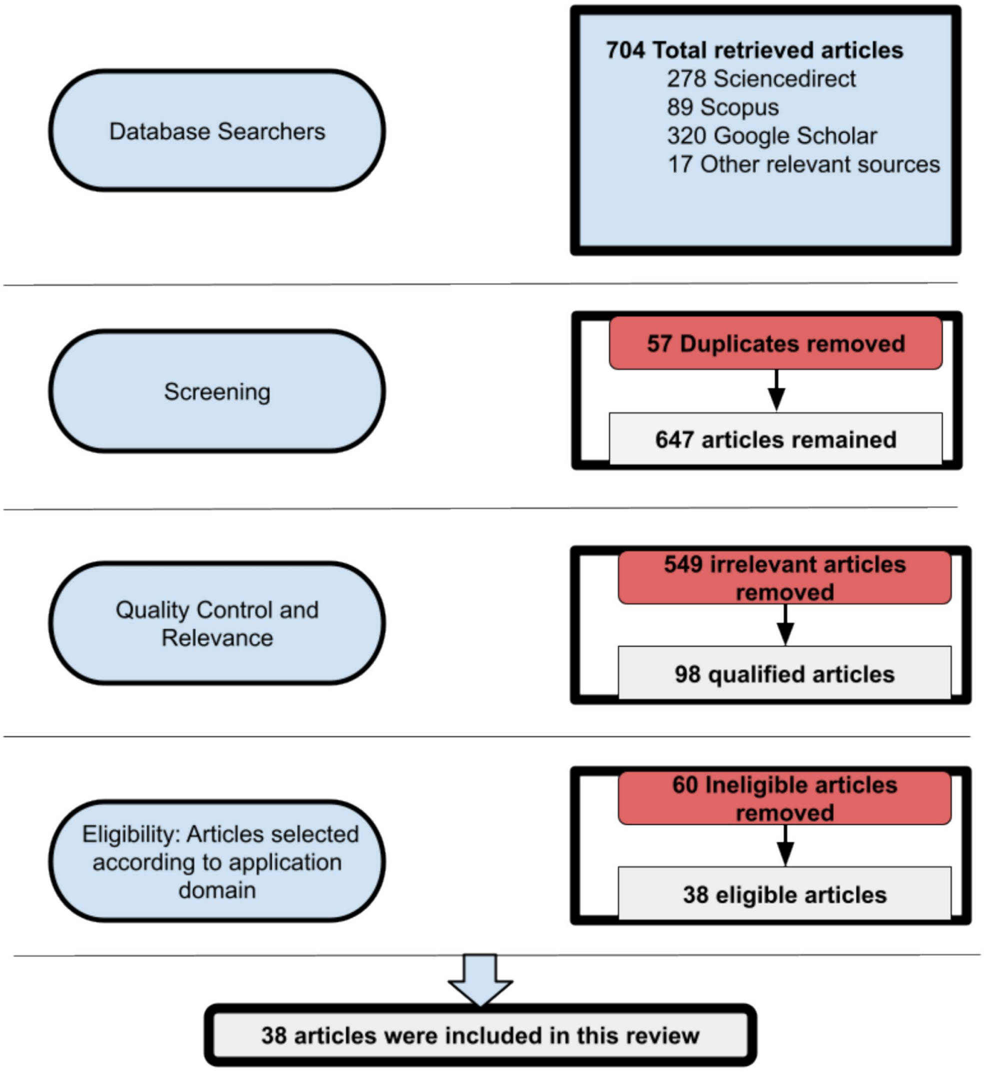

FIGURE 1
PRISMA flow diagram for this review. A total of 704 articles were collected and 38 articles were selected for review after screening.

fertilization in East Africa. Tables 1, 2 summarizes these constructs, technologies, benefits, challenges, and key stakeholders.

- Among the studies reviewed, 43% center on mobile applications such as SoilDoc, the Fertilizer Optimization Tool (FOT), and SoilCares. These applications offer real-time soil analyses and personalized fertilizer recommendations to assist farmers. The reported benefits of these mobile applications include enhanced nutrient management and crop productivity. However, the studies also emphasized that limited access to these tools persists due to cost and infrastructure constraints, particularly in rural areas, thereby constraining adoption among smallholder farmers.
- 30% of the studies focus on ICT tools like soil sensors, GPS mapping, and UAVs. These tools help to assess soil moisture, temperature, and crop health, allowing for more precise and efficient fertilizer applications. This not only reduces input waste but also minimizes environmental impact. However, the adoption of ICTs faces barriers such as high costs and the technical expertise required for use and maintenance. This can limit accessibility for smallholder farmers and community cooperatives.
- Variable rate application (VRA) is highlighted in 20% of the studies as a practice that allows for the differential application of fertilizer based on soil variability across field zones. Research indicates that VRA contributes to increased yield and profitability, particularly for maize and rice crops, while also reducing nutrient runoff for the benefit of soil and water health. However, the high initial cost and calibration requirements of VRA technology make it financially unattainable for many smallholder farmers, thus limiting its widespread adoption.
- In 27% of the studies, AI and ML technologies have been found to enhance decision-making in fertilizer applications by analyzing intricate datasets related to soil, crops, and climate. For instance, research conducted in Kenya and Rwanda has demonstrated that AI-driven recommendations have led to improved yields by optimizing the timing and quantity of fertilizer usage. However, challenges such as data privacy issues and potential biases in algorithmic

TABLE 1 Summary table showing the current state of art for the adoption of precision fertilization technologies in East Africa.

No.		Technology	Function/activity	References
1a	Mobile apps	SoilDoc App	The app recommends the appropriate type and amount of fertilizer to apply in the soil after analyzing different parameter in the soil by using machine learning algorithms	Dimkpa et al. (2017)
1b		Fertilizer Optimization Tool (FOT)	The app provides customized fertilizer recommendations to farmers based on the crop type, soil type and other factors. It also offers the farmer a chance to compare the cost-effectiveness of different fertilizer options	Rware et al. (2019)
1c		SoilCares	The app provides customized fertilizer recommendations by measuring soil properties and comparing the data obtained to the information in the digital soil database that covers East African countries	Dimkpa et al. (2017)
1d		Yara imageIT	The app recommends the suitable amount of nitrogen to achieve maximum yield by measuring the nitrogen uptake in the crop	Ogunti et al. (2018)
2a	ICTs	Soil sensors	Soil sensors are among the common ICT tools used in East Africa to measure soil moisture, temperature, and nutrient levels, which helps farmers in their fertilizer application decisions	Piikki et al. (2016) and Yousfi et al. (2019)
2b		Satellite images	By using satellite images different production restraints related to soil fertility and nutrient deficiencies can be assessed and fixed accordingly	Mwendwa et al. (2022)
2c		UAV and drones	UAVs and drones are used for remote sensing of crop health and nutrient levels to help in fertilizer application	Soesilo and Rambaldi (2018)
3	VRA technique		A study found that VRA has a potential to increase rice yield and improve profitability for smallholder farmers in sub-Saharan Africa	Tsujimoto et al. (2019)
			Another study in Ethiopia found that the use of VRA in fertilizer application resulted in a higher net profit for maize farmers compared to the conventional broadcasting methods	Alemaw and Agegnehu (2019)
4	AI and ML		An AI-based smart system that can advise maize-growing farmers on the type and amount of fertilizer to use for increased yield was developed in Kenya	Mwangi and Kamau (2016)
			A model with performance of 91.7% for smart fertilization and irrigation was developed in Rwanda by integrating IoT and deep learning	Nyakuri et al. (2022)
			Soil nutrient development models were developed the ensemble ML approach under the Optimizing Fertilizer Recommendations in Africa (OFRA) project in Rwanda	Uwiragiye et al. (2022)

recommendations still exist. These limitations underscore the necessity for frameworks that address data ownership, ethical considerations, and localized model training to ensure accuracy. Most recently, authors discussed in 27% of the studies that artificial intelligence (AI) and machine learning (ML) technologies improve decision-making in fertilizer applications by analyzing soil, crop, and climate data. Studies from Kenya and Rwanda showed promising results in enhancing yield through optimized fertilizer recommendations, although limitations include data privacy concerns and algorithm biases.

3.2 Quantitative summary

Of the 38 studies included in this review, the majority (53%) were empirical studies, 34% were case studies, and 13% were systematic reviews focused on the impact of digitalization in precision fertilization within specific East African contexts. Geographically, most studies were conducted in Kenya, Tanzania, and Rwanda, suggesting a need for expanded research on precision agriculture technologies in other East African countries with distinct agroecological zones and varying levels of agricultural infrastructure.

3.3 Limitations in current literature

Our analysis reveals several limitations in the existing literature. First, a significant gap exists in long-term studies assessing the lasting impacts of digital precision fertilization on soil health, crop productivity, and environmental sustainability. Additionally, research on the scalability of these technologies across diverse East African settings is sparse, limiting our understanding of how digital tools might perform under different socioeconomic and agroecological conditions. Future studies should also aim to increase the sample size and include a wider range of regions to better capture the variability in digital agricultural practices across East Africa.

4 Scope and status of precision fertilization in East Africa

Precision fertilization is an innovative farming practice that aims to increase crop yields and reduce fertilizer use by tailoring the nutrient application to the specific needs of individual plants or fields (Schimmelpfennig, 2018). Figure 2 depicts an overview of the precision fertilization process. Despite the potential benefits of precision fertilization, its adoption in developing countries, especially East African countries, is still in its early stages. However, there is growing interest and investment in the technology from governments, research institutions, and private sector players. A study by Nguyen et al. (2023) identifies several factors hindering the adoption of this technology in developing countries, including the technical complexity, limited access to capital and credit, inadequate infrastructure, and lack of technical knowledge and awareness among farmers. Several initiatives have been launched to address these challenges and promote the adoption of precision fertilization in East Africa. For example, the African Plant Nutrition Institute has established a program to train extension workers and farmers on precision fertilization technologies. Similarly, the Alliance for a Green Revolution in Africa has launched a project to promote precision fertilization among smallholder farmers in Kenya and Tanzania.

Overall, the literature suggests that precision fertilization is promising for improving agricultural productivity, sustainability, and environmental outcomes in East Africa. While several challenges remain, the concerted efforts of various stakeholders bode well for the technology's future adoption and expansion.

4.1 Adoption of mobile apps in precision fertilization in East Africa

While the use of mobile phones has been everyday in developed countries for decades, developing countries, especially East African countries, have only recently seen a surge in mobile phone usage. In Tanzania's example, there has been a rapid increase in mobile phone usage, with over 57 million cellular mobile connections nationwide, equivalent to 86% of the total population. Evidence shows that mobile phones have helped to improve the livelihoods of poor and marginalized people in Tanzania (Baird and Hartter, 2017). A study examining the relationship between mobile phone usage and smallholder agricultural productivity in Tanzania revealed that farmers who owned and used mobile phones to get different agricultural information services significantly increased their agricultural productivity compared to their counterparts (Quandt et al., 2020). Another similar study by Krell et al. (2021) found that smartphones were a significant factor in accessing agricultural information services in Kenya. With the rise of smartphone technology, a new generation of mobile apps has emerged that can help farmers implement precision agriculture more effectively. These apps use advanced sensors, data analysis, and machine learning algorithms to provide farmers with real-time information and recommendations on fertilizer application, irrigation, and other essential factors that affect crop growth (Mendes et al., 2020).

One such app is the SoilDoc app, a mobile integrated package for soil fertility management developed collaboratively by the Agriculture and Food Security Centre of Columbia University New York and the University of Maryland (Dimkpa et al., 2017). The app uses a mobile phone camera to capture images of soil samples for assessing different soil parameters, including biologically active soil organic matter; soil moisture and texture; pH; and extractable macronutrients, nitrate-N, phosphate-P, potassium-K, sulfate-S, which are then analyzed using machine learning algorithms to provide information on soil fertility and nutrient content. This information recommends the appropriate type and amount of fertilizer to apply.

Another app is the Fertilizer Optimization Tool (FOT), developed by the Alliance for a Green Revolution in Africa (AGRA). The app provides customized fertilizer recommendations to farmers based on the crop, soil type, and other factors. The app also allows farmers to compare the cost-effectiveness of different fertilizer options, which helps farmers maximize their net return from fertilizer investments (Rware et al., 2019).

SoilCares is another mobile app that analyzes soil samples to provide farmers with customized fertilizer recommendations. The app uses advanced technology to measure soil properties such as pH, organic matter, and nutrient levels. This data is then compared to the information in the digital soil database that covers the East African countries of Tanzania, Kenya, Uganda, Rwanda and Burundi (Dimkpa et al., 2017).

Fertilizer recommendations can also be made based on the plant's appearance. Yara imageIT is a farming App that uses crop photographs to measure the nitrogen uptake in the crop and recommend the suitable amount of nitrogen to achieve maximum yield. This App calculates nitrogen uptake based on the leaf's green color (green area index), leaf cover (leaf area index), and the estimated fraction of brown leaves (Ogunti et al., 2018). These are just a few examples of mobile apps used in precision fertilization in East Africa. Other apps and technologies are also being developed to help farmers improve crop yields and reduce fertilizer waste.

4.2 Adoption of ICTs in precision fertilization in East Africa

The application of (ICTs) has revolutionized the way precision fertilization is carried out, enabling farmers to make informed decisions based on real-time data about their crops and the soil (Demestichas and Daskalakis, 2020). By using sensors, drones, GPS mapping, and other ICT tools, farmers can accurately assess the nutrient needs of their crops and apply fertilizers in a targeted manner, reducing waste and environmental impact while improving productivity and profitability. In recent years, the adoption of (ICTs) has enhanced the practice of precision fertilization in East Africa. Soil sensors are a standard ICT tool used in precision fertilization in East Africa. They measure soil moisture, temperature, and nutrient levels, providing farmers with real-time data to inform their fertilizer application decisions (Piikki et al., 2016). Studies have shown that using soil sensors can significantly increase crop yields while reducing fertilizer application, leading to more sustainable agriculture (Yousfi et al., 2019). Satellite images have shown potential for assessing the spatial variability of selected soil properties, which helps to determine the production restraints related to soil fertility and fix nutrient

TABLE 2 Benefits and drawbackds of the tecprecision technologies.

Construct	Digital technology	Benefits	Drawbacks	Stakeholders	Source(s)
Precision fertilization	Mobile Apps (e.g., SoilDoc, FOT)	Enhanced nutrient management, real-time soil analysis	Limited access, high costs, digital literacy requirements	Smallholder Farmers, NGOs	Finger et al. (2019) and Krell et al. (2021)
Crop monitoring	ICT Tools (e.g., soil sensors, GPS, UAVs)	Improved data for targeted fertilization, reduced input waste	Technical expertise needed, high initial cost	Extension Services, Local Gov.	Mapiye et al. (2021) and Yousfi et al. (2019)
Variable rate application	VRA technology	Increased yield and profitability, reduced nutrient runoff	Prohibitive cost for smallholders, calibration issues	Farmers, Agribusinesses	Tsujimoto et al. (2019) and Alemaw and Agegnehu (2019)
Predictive fertilization	AI and ML algorithms	Optimized fertilizer application timing and amounts, reduced cost	Data privacy concerns, potential algorithm bias	Researchers, Tech Developers	Mwangi and Kamau (2016) and Nyakuri et al. (2022)
Soil health assessment	Satellite Imaging	Broad area monitoring, improved identification of nutrient deficiencies	Limited resolution, accessibility constraints	Regional Gov., NGOs	Mwendwa et al. (2022) and Soesilo and Rambaldi (2018)
Crop yield optimization	Deep learning (DL)-based IoT	High accuracy in smart fertilization and irrigation applications	Limited internet, high costs, technical skill required	Farmers, Researchers	Uwiragiye et al. (2022) and Linaza et al. (2021)
Water & soil management	Drone surveillance	Real-time crop health assessment, reduced environmental impact	Cost of UAV technology, regulatory restrictions	Environmental NGOs, Farmers	Vatsanidou et al. (2020) and Protopop and Shanoyan (2016)
Digital extension services	Smartphone applications	Easy access to advisory services, weather alerts, and crop management tools	Limited rural connectivity, device compatibility issues	Farmers, Extension Workers	Krell et al. (2021) and Quandt et al. (2020)
Fertilizer recommendation	Machine learning (ML) models	Data-driven recommendations for fertilizer optimization	Requirement for high-quality data, complex model training	Tech Developers, NGOs	Beverley and Thakur (2021) and Dara et al. (2022)

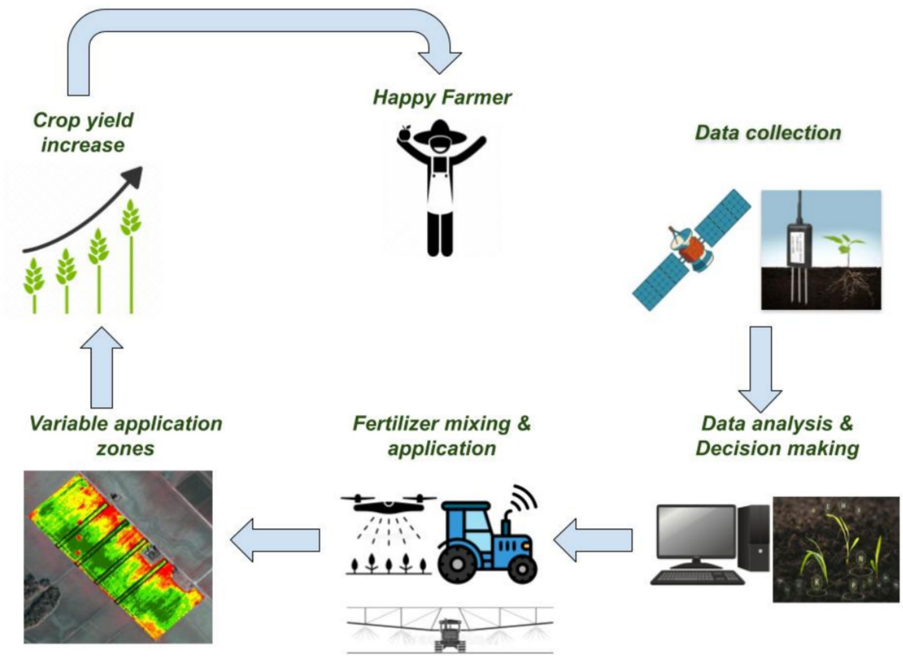

FIGURE 2
An overview of the precision fertilization process.

deficiencies (Mwendwa et al., 2022). Additionally, unmanned aerial vehicles (UAV) and drones for remote sensing of crop health and nutrient levels have also been adopted in precision fertilization in East Africa. The data collected by UAVs and drones can be used to inform fertilizer applications, making the process more precise and efficient (Soesilo and Rambaldi, 2018).

4.3 Adoption of VRA in precision fertilization in East Africa

VRA enables farmers to apply different rates of fertilizers to various parts of their fields, depending on the soil fertility and nutrient needs of the crops. This targeted application of fertilizers improves crop yields, reduces fertilizer use and cost, and minimizes environmental impacts such as nutrient runoff and leaching (Gorai et al., 2021). VRA is becoming increasingly popular in many regions, including East Africa, where smallholder farmers dominate the agricultural landscape. Lack of fertilizer inputs and nutrient-poor soils are among the challenges to smallholder farmers' rice production in sub-Saharan Africa (SSA). A study by Tsujimoto et al. (2019) discussed the importance of improving nutrient efficiency in increasing fertilizer usage and rice yield. The study recommends the utilization of VRA to achieve this objective. In addition to increasing crop yields and reducing fertilizer use, VRA has also improved profitability for smallholder farmers. A study in Ethiopia found that using VRA to apply fertilizer resulted in higher net profits for maize farmers than conventional broadcasting methods (Alemaw and Agegnehu, 2019). VRA also has the potential to improve environmental sustainability by reducing fertilizer runoff and leaching. A study by Vatsanidou et al. (2020) found that using VRA to apply fertilizer reduced nutrient runoff significantly compared to conventional broadcasting methods. The study also found that VRA reduced soil acidity, which can lead to reduced crop yields and environmental degradation. While the adoption of VRA in East Africa is increasing, there are still challenges to overcome. One of the main challenges is the cost of the machines, which can be prohibitive for smallholder farmers. Another challenge is the need for technical expertise to operate and maintain the machines, which may not be available in all areas. Finally, there is a need for more research on the long-term impacts of VRA on soil health and environmental sustainability.

4.4 Adoption of AI and ML in precision fertilization in East Africa

AI and ML significantly improve precision fertilization by analyzing data from various sources, such as soil and weather sensors, drones, and satellite imagery. The analyzed data can then be used to create predictive models that can optimize fertilizers' amount, timing, and placement (Linaza et al., 2021). In recent years, these technologies have been increasingly adopted in precision fertilization to improve crop yields, reduce costs, and mitigate environmental impacts. Several studies have investigated the potential of these technologies in precision fertilization in East Africa. Mwangi and Kamau (2016) collected data from small-scale and large-scale farmers in some maize-growing regions in Kenya to develop an AI-based innovative system with reasoning capabilities through knowledge basis and advice Kenyan farmers on the amount and type of fertilizer to use on their farms to increase yield. Another study was conducted by Nyakuri et al. (2022) to optimize fertilizer use while increasing yield production in the Eastern province of Rwanda. The study investigated the integration of IoT and a deep learning (DL) driven solution for smart fertilization and irrigation by assessing soil nutrients and soil water content dynamics. The study's findings showed that the model could perform well with an accuracy of 91.7%, and it can work well in different environments even when deployed in remote areas with minimum internet connection. Another study done by Uwiragiye et al. (2022) used the ensemble ML approach to develop soil nutrient development models. The study was conducted under the Optimizing Fertilizer Recommendations in Africa (OFRA) project in Rwanda. The study revealed that the ensemble ML model outperformed single models in predicting soil nutrient balance.

Overall, the literature suggests that AI and ML technologies have great potential to improve precision fertilization in East Africa. By using advanced data analysis techniques and predictive models, farmers can optimize fertilizer usage and reduce costs while minimizing environmental impact. However, further research is needed to explore the scalability and effectiveness of these technologies across different crops and regions in East Africa.

5 Benefit of mobile apps, ICTs, VRA, and AI & ML in precision fertilization

Precision fertilization is a technology-driven approach that enables farmers to optimize crop yield, minimize fertilizer usage, and reduce environmental pollution. In East Africa, the adoption of (ICTs), mobile apps, VRA, and AI and ML are revolutionizing precision fertilization, bringing numerous benefits to farmers. One of the key benefits of the adoption of these technologies in precision fertilization is enhanced efficiency (Kolmykova et al., 2021). These technologies enable farmers to remotely monitor crop growth, soil conditions, and weather patterns, allowing for timely interventions. For instance, a mobile app like FarmForce enables farmers to track crop growth, record fertilizer applications, and receive weather alerts, among other things (Protopop and Shanoyan, 2016). VRA, on the other hand, enables farmers to apply fertilizers at different rates depending on the needs of the crops and soil. This precision application reduces fertilizer wastage and optimizes crop yields.

Another benefit is improved data analysis. Precision fertilization generates vast amounts of data on soil conditions, crop growth, and fertilizer usage, which can be overwhelming for farmers to analyze. However, AI algorithms can analyze this data quickly, identifying patterns and trends that can inform better decision-making. For example, AI-powered precision fertilization systems like Plantix use ML algorithms to analyze data on soil conditions, crop growth, crop nutrient deficiencies, and weather patterns, recommending fertilizer application rates based on this analysis (Beverley and Thakur, 2021).

Moreover, the adoption of these technologies in precision fertilization promotes environmental sustainability. The precise application of fertilizers minimizes fertilizer runoff, which can pollute water sources, degrade soil quality, and harm aquatic life. Additionally, remote monitoring and data analysis enable farmers to adopt sustainable farming practices, such as crop rotation and cover cropping, which enhance soil fertility and reduce the need for fertilizers.

Lastly, adopting ICTs, mobile apps, VRA, and AI and ML in precision fertilization creates economic opportunities for farmers. These technologies enable farmers to optimize crop yields, reducing input costs and increasing profits. Additionally, the data generated by precision fertilization systems can inform better marketing strategies, allowing the farmers to target specific markets and negotiate better prices for their crops.

6 Drawbacks of the adoption of these digital technologies in precision fertilization

So far, we have seen the potential mobile Apps, ICTs, VRA, AI, and ML have in revolutionizing precision fertilization. However, there are some losses associated with the adoption of these technologies. One of the significant drawbacks is technical-related losses that may occur when using these technologies. Using ICTs requires reliable and accurate data from sensors and other devices (Misra et al., 2016). Unfortunately, in East Africa, there is a lack of up-to-date data on soil nutrient content, weather patterns, and crop yields (Huadong, 2018). Without accurate and reliable data, making informed decisions on the optimal amount and timing of fertilizer application is challenging. This can lead to either under-fertilization, which results in reduced crop yields, or over-fertilization, which leads to environmental pollution and soil degradation. Also, technical issues such as sensor malfunction or data inaccuracies can lead to incorrect fertilizer applications. A study by Berazneva et al. (2018) highlights the need for more investment in soil testing facilities and data collection systems to provide farmers with reliable information on soil nutrient content and crop performance. ICTs and mobile apps in precision fertilization also face technical challenges, such as limited internet connectivity, device compatibility, and software glitches. For instance, using mobile apps for data collection and analysis requires reliable internet connectivity, which is limited in many rural areas in East Africa. In addition, the compatibility of mobile apps with different types of devices and operating systems can lead to technical glitches that affect data accuracy and reliability. Another technical challenge is the lack of standardization in precision fertilization technologies, particularly in VRA. VRA machines apply fertilizers at variable rates depending on the soil nutrient content and other factors, which require accurate and precise calibration. However, the lack of standardized calibration procedures and guidelines can result in inaccurate fertilizer application, reducing crop yields and increasing fertilizer costs.

Data privacy and security are other drawbacks of adopting these technologies in precision fertilization. Using these technologies requires collecting and sharing sensitive data such as soil composition, crop growth, and fertilizer applications. The storage and transfer of this data can be vulnerable to hacking or data breaches, which can compromise farmer privacy and security. The limited awareness among farmers and other stakeholders about the risks and vulnerabilities of precision fertilization technologies and the absence of clear data protection laws and policies expose farmers' data to risks such as unauthorized access, data breaches, and cyber-attacks. This can lead to inadvertent disclosure of sensitive data, which can be used maliciously. Mobile apps also face data privacy and security challenges, such as data leakage, unauthorized data access, and data sharing. Mobile apps collect and store farmers' data, including personal information, financial data, and location data, which can be sensitive and require protection from unauthorized access. Finally, using AI and ML in precision fertilization raises data privacy and security concerns such as algorithm bias, data ownership, and data breaches. The effectiveness of AI and ML models in precision fertilization depends on the quality and quantity of data used to train them. However, the ownership of data collected from precision fertilization technologies is unclear, leading to disputes over data ownership and usage rights. In addition, using AI and ML models can lead to algorithm bias, resulting in unfair and discriminatory decision-making. A study by Dara et al. (2022) recommends developing ethical guidelines for using AI and ML in precision fertilization to ensure fairness, accountability, and transparency in decision-making.

Environmental concern is another challenge associated with adapting these technologies in precision fertilization. Precision fertilization technologies can lead to more accurate fertilizer application, reducing the use of fertilizers and minimizing environmental pollution. However, adopting these technologies also requires proper management practices to prevent the accumulation of excess fertilizers in soil and water. Overusing or misusing fertilizers can lead to environmental problems such as soil degradation, water pollution, and greenhouse gas emissions. On the other hand, precision fertilization involves using sensors, GPS, and other electronic devices that can potentially increase energy consumption and greenhouse gas emissions.

Precision fertilization technologies generate large amounts of data on soil quality, crop yield, and fertilizer application rates. This data can be valuable for decision-making and improving agricultural practices. However, private companies or government agencies may own and control this data, which can limit farmers' access to it. This can reduce transparency and accountability, impacting farmers' ability to make informed decisions.

Precision fertilization tools and technologies can be complex, and their successful implementation requires high technical expertise. The complexity of these systems can be a barrier for some farmers, particularly those with limited technical knowledge or access to training. Nevertheless, the complexity of precision fertilization technologies can lead to unintended consequences and negative externalities. Using AI and ML in precision fertilization can lead to developing complex algorithms that may not account for local environmental and socio-economic contexts. This can lead to suboptimal fertilization practices with unintended environmental and social consequences.

Finally, the use of AI and ML in precision fertilization can raise ethical concerns about the impact of these technologies on the environment. AI and ML can lead to the development of precision fertilization technologies that can increase agricultural productivity while reducing the environmental impact of fertilizers. However, using these technologies can also lead to the automation of agricultural practices, which can displace farm labor and affect the socioeconomic well-being of farmer workers. A study by Dara et al. (2022) recommends developing ethical guidelines for using AI and ML in agriculture that can ensure the protection of the environment and the socio-economic well-being of farmer workers.

7 Conclusion

This review highlights several important research gaps, including the necessity for longitudinal studies on the environmental and economic impacts of precision fertilization technologies. Additionally, further investigation into technology scalability, data privacy, and socioeconomic barriers in East Africa is crucial to developing sustainable and inclusive digital agriculture solutions. The review emphasizes the significant potential of digital tools—such as mobile applications, ICTs, VRA, AI, and ML—in advancing precision fertilization in East Africa. While current literature demonstrates benefits such as improved yield, efficiency, and sustainability, adoption remains hindered by high costs, limited digital literacy, and infrastructure challenges. The findings also point out methodological gaps within the reviewed studies, including smaller sample sizes, regional bias, and lack of standardized reporting on digitalization impacts across East Africa. Future research should prioritize empirical studies with broader geographic and linguistic scope, addressing socio-economic barriers that hinder technology adoption.

8 Recommendations and future research

Our review was based on a limited number of open-access papers and databases. However, we recommend that studies expand their coverage to include additional countries and a more diverse range of agroecological zones within East Africa. Furthermore, it is crucial to delve into long-term studies on the impact of digital technology on soil health and crop yield. Given the potential for digital technology to compromise privacy and security in Africa, it is imperative to conduct further research addressing data privacy, security concerns, and ethical considerations associated with AI and ML in precision agriculture.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

KF: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Validation, Visualization, Writing – original draft, Writing – review & editing. GB: Methodology, Validation, Writing – review & editing, Data curation, Investigation, Project administration. OJ: Methodology, Validation, Writing – review & editing, Conceptualization, Supervision. SB: Conceptualization, Funding acquisition, Investigation, Project administration, Supervision, Writing – review & editing. LK: Conceptualization, Funding acquisition, Investigation, Supervision, Writing – review & editing.

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Conflict of interest

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

Publisher's note

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