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Bespoke Precision Agriculture for Small-Scale Farming in Sub-Saharan Africa: Defining Potential Benefits and Pathways

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ABSTRACT

Precision agriculture (PA) holds enormous potential for smallholder farmers in sub-Saharan Africa (SSA), where agriculture remains central to economic development, employing more than half of the adult population and contributing significantly to GDP. However, adoption rates remain low. This communication examines the potential benefits, challenges and possible pathways for increasing uptake among smallholders in SSA. Drawing from recent initiatives and case studies, successful applications demonstrate that low-cost, localised and gender inclusive PA innovations can increase adoption among smallholders. However, challenges such as high upfront technology costs, limited internet connectivity, low digital literacy, limited access to financial services and a lack of tailored training remain significant barriers. Addressing these barriers requires the co-creation of affordable technologies and flexible financing schemes, the provision of support services, offline functionality and integrating PA into the educational curriculum and extension systems in SSA to build capacity to sustain adoption. Furthermore, promoting gender inclusivity and strengthening data management systems are equally important for long-term success. By addressing these barriers, PA can drive sustainable agricultural production, improve food security and enhance climate resilience. This communication highlights the need for coordination among farmers, developers, researchers and policymakers to foster a robust PA ecosystem for smallholder farmers in SSA.

JEL Classification: O13, O33, Q16, J16

1 | Introduction

In sub-Saharan Africa (SSA), agricultural production is one of the most important economic sectors of many countries (Nyaga et al. 2021). Agriculture in SSA is dominated by smallholder farmers (Aduramigba-Modupe and Oke 2024; Abay et al. 2023; Oumer et al. 2020; Berger et al. 2017), employing 52% of the adult population and contributing to around 17% of the gross domestic product (GDP) of the region (World Bank 2021, 2022a). However, despite the important role of the agricultural sector to the economic development of the region, the sector is inherently characterised by low productivity and low income for farmers (e.g., Abay et al. 2023; Marinus et al. 2022; Mulwa et al. 2021; Ariga et al. 2019; Scheiterle et al. 2019), making it unattractive for young people entering the workforce. A plausible reason for the low productivity and low income for farmers in the agricultural sector in SSA could be attributed to the use of old and rudimentary methods of farming. Rapid population growth in the region in recent decades (World Bank 2022b), coupled with climate change, makes the adoption of innovative agricultural technologies an imperative to meet food demand in the region. One possible pathway to improve agricultural productivity and profitability, and to incentivise the youth in the region to take up agricultural production, is through the adoption of precision agriculture (PA).

According to the International Society of Precision Agriculture (ISPA) (2024), PA is defined as 'A management strategy that gathers, processes and analyses temporal, spatial and individual plant and animal data and combines it with other information to support management decisions according to estimated variability for improved resource use efficiency, productivity, quality, profitability and sustainability of agricultural production'. PA aims to improve agricultural production by spatially deploying inputs to where and when they are most productive, thereby optimising overall output for the given inputs (DeLay et al. 2022). Accordingly, it is established that PA can enhance farming efficiency, crop production, reduce environmental impacts of farming and enhance farm profitability (e.g., Wang et al. 2023; Khanna et al. 2022; DeLay et al. 2022; Finger et al. 2019). Importantly, PA also has the potential to reduce some of the environmental pressures associated with agricultural intensification in SSA. For example, remote sensing and machine-learning approaches have been used to identify spatial variability in soil salinity, nitrate levels and moisture, enabling more targeted irrigation and fertiliser management and reducing unnecessary input use (Otoro and Komai 2025). Similarly, machine-learning models that integrate environmental and climate data can improve crop-yield predictions, supporting more informed management decisions and lowering environmental impacts (Olatinwo et al. 2026). Drone technologies can also facilitate earlier pest detection and precise crop monitoring, reducing reliance on blanket pesticide applications in smallholder farming systems (Ahmed et al. 2026).

Despite the promise of PA technologies, the adoption rate remains low for small and medium farms in developing countries (e.g., Lowenberg-DeBoer and Erickson 2019). John et al. (2023) and Nyaga et al. (2021) suggest that high upfront costs, lack of awareness and lack of information about PA are some of the main reasons for the limited adoption of PA among smallholder farmers in developing countries. Thus, to increase the adoption of PA among smallholders in SSA, there is the need to create awareness and educate farmers and agricultural stakeholders in the region with the necessary information and knowledge about PA, including a better understanding of its potential benefits for smallholder farmers.

Previous studies on PA have generally focused on large scale farming and its ability of PA to improve farm productivity and profitability (e.g., Saha et al. 2025; Sanyaolu and Sadowski 2024; Wang et al. 2023; Parikoglou et al. 2022; Aune et al. 2017), adoption decisions (e.g., Thangamani et al. 2025; John et al. 2023; Kendall et al. 2022; DeLay et al. 2022; Lowenberg-DeBoer and Erickson 2019), the potential and challenges of PA for farmers (e.g., Spagnuolo et al. 2025; Khanna et al. 2022; Bosompem 2021; Nyaga et al. 2021; Ofori and El-Gayar 2021), smart sensor technologies and internet of things (e.g., Aarif et al. 2025; Singh and Sharma 2025; Mansoor et al. 2025) and the role of data or data management for the deployment of PA (e.g., Gobezie and Biswas 2023). Up until now, little is known about the potential of PA for smallholder farmers (e.g., John et al. 2023; Mizik 2023; Kendall et al. 2022), particularly for smallholder farmers in SSA. While studies exist on PA in SSA (e.g., Fue et al. 2025; Bashiru et al. 2024; Nyaga et al. 2021; Bosompem 2021; Aune et al. 2017), they rarely concentrate solely on smallholder farmers in the region.

The objective of this communication is to highlight the potential of PA for smallholder farmers in SSA. This paper will provide practical examples of successes and failures of PA initiatives for smallholders in the region, the role of PA data for decision-making and provide insights into the economics of PA. Furthermore, the need for integration of PA into the educational curriculum in SSA will be highlighted and issues relating to the adoption of PA in the smallholder-farm setting in SSA will be discussed. Improving the understanding of the potential benefits and issues relating to the adoption of PA by smallholder farmers in SSA will be of interest to farmers, agri-tech entrepreneurs, researchers and policymakers alike.

2 | Successes and Failures of Precision Technology for African Smallholder Farmers

Given PA's increasing popularity as a farm management strategy, its application to smallholder farming systems has not been well documented. This is particularly the case in SSA and in the context of successes and failures, and the lessons learned to guide future initiatives and enhance adoption.

A key success of PA technologies among smallholder farmers in SSA has been the deployment of mobile-based applications (apps) and services (e.g., Emeana et al. 2020; UNDP 2021). A leading example is the PlantVillage Nuru app (hereafter, PlantVillage) (UNDP 2021). This digital platform enables farmers to access expert advice on pest and disease management enabling timely management decisions. To use this service, farmers need to take a picture of the affected crop(s), upload them to the digital platform and wait for a diagnosis from a plant disease expert. Since its launch in 2018, PlantVillage has aggregated over 50,000 infested plant images, becoming one of the largest open-access crop health knowledge libraries in the world (UNDP 2021). The platform has forum rooms to enable information sharing and peer-to-peer discussions. Additionally, PlantVillage has a digital assistant, Nuru, which enables farmers to receive an artificial intelligence (AI) identification of suspected diseases if needed. It can diagnose diseases in maize, cassava, wheat and potato (UNDP 2021). The application can work without the internet by relying on its in-built AI model to diagnose pests and diseases. However, internet connectivity is required if expert advice is needed. The application has been proven to be twice as accurate as extension workers (UNDP 2021), helping farmers in the region to increase yield by up to 30% and increasing farmers' income by $300 annually through effective pest and disease management (iAfrica 2025).

Similarly, another PA technology tested to a greater extent among smallholder farmers in SSA is drip/smart irrigation (e.g., Onyango et al. 2021; Wanvoeke et al. 2015). Farming systems in SSA are predominantly rainfed, making them susceptible to climate variability (Nigussie et al. 2020). A drip irrigation system can help improve spatial and temporal water management, water use efficiency and enhance climate resilience among smallholder farmers in SSA (Mume et al. 2023; Aduramigba-Modupe and Oke 2024). In recent years, several precision drip irrigation projects have been implemented in SSA by national governments and development partners to enhance agricultural productivity among smallholder farmers in the region (e.g., Muturi et al. 2019; Alaofè et al. 2016). For example, the Smart Water Agricultural Project (SWA) is a Dutch government-funded project that focuses on the needs and opportunities of Kenyan small and medium-sized farmers with as little as 0.1 to 5 ha (ha) of irrigated land, focused on growing high-value crops (Muturi et al. 2019). Launched in 2016, SWA, a four-year initiative, primarily aimed to promote farmer-led irrigation development, including solar-powered pumps, drip irrigation kits, finance, water storage systems and training, ensuring that farmers in the country could adopt and sustain precision irrigation technologies even after the end of the project. Following a farmer-led approach (Mati 2023), SWA collaborated with local suppliers to extend its network into rural areas. Farmers were linked to suppliers through training programmes (e.g., operation and maintenance), field demonstrations and irrigation acceleration platforms. Furthermore, local service providers were trained and certified to install and maintain kits, ensuring that after-sales support was available to adopters (Muturi et al. 2019). Financing of the drip irrigation equipment was possible through SWA's specially designed loan products, pay-as-you-go models and co-financing schemes through microfinance institutions and banks in the country (Kariuki et al. 2020). These approaches, particularly the pay-as-you-go-model, allow the supplier to install the drip irrigation equipment on the farmer's plot, so the farmer starts using it immediately. However, instead of the farmer paying the full cost of the equipment upfront (e.g., USD $500), the farmer pays a small deposit (e.g., 10%–20% of the cost) and the remaining cost is paid to the supplier in regular instalments over an agreed period.

Following installation, depending on the size of the farm, farmers employ either simple timers and manual irrigation scheduling or more advanced sensor-based controllers that integrate soil moisture and weather data to automate irrigation. In some cases, fertigation units allow soluble fertilisers to be directly injected into the drip system, improving nutrient use efficiency (e.g., Yang et al. 2024). Since the project started, 19,000 farmers (40% women) have been reached and 7500 farmers have adopted at least one of the promoted technologies, including drip and micro-irrigation systems, solar-powered pumps, low-pressure sprinklers, automated water management systems, water pans and rain-harvesting structures, soil moisture sensors, among others (Muturi et al. 2019). The success story is significant. Adopters of the various technologies reported a 30%–50% reduction in water usage and a 20% increase in cabbage and tomato production, resulting in €100 additional seasonal income for smallholders cultivating <1 ha compared to non-adopters (Muturi et al. 2019). Furthermore, 12,500 farmers had access to finance from at least five financial services providers to adopt the promoted technologies and to expand their farm operations (SNV 2016), a critical limiting factor for farmers and agricultural development in SSA (e.g., Asiseh et al. 2025; Shuaibu and Nchake 2021).

Apart from pest and disease management PA technologies (e.g., PlantVillage) and drip irrigation systems, soil sensing/testing kits are also widely used among smallholder farmers in SSA to make site-specific fertilisation decisions (IFDC 2017). The rapid population growth in SSA in recent decades, coupled with climate change, threatens food security in the region (Hall et al. 2017). Increasing fertiliser use and sustainable intensification of agricultural production in the region are necessary to meet the food demands of the population (Holden 2018). However, existing evidence suggests that blanket fertiliser applications commonly used in SSA are less efficient due to the spatial variability of soil nutrients or site-specific differences in soils in the region (e.g., Soropa et al. 2023; Onyango et al. 2021). To improve the situation, soil testing is the starting point (Simonne et al. 2017), to determine which areas of the field need fertilisation, the type of fertiliser needed based on the crop and the amount required for optimum production. For example, in Ghana, commercial soil-testing services such as FarmSense, Demeter Ghana Limited (hereafter Demeter) and the International Fertiliser Development Centre (IDFC) supported projects have become entry points for smallholder farmers to use PA. These service providers offer affordable soil diagnostics using portable soil-testing kits (e.g., Hach, SoilDoc) (IDFC 2017) or mobile lab soil-testing equipment (Demeter Ghana Limited 2025a). For example, to use the services of Demeter, a farmer contacts the service provider for soil sample collection. Following sample collection, the soil is tested and analysed for key soil parameters at the organisation's laboratory. Demeter has the capacity to test for a wide range of soil parameters, including soil nitrogen, potassium, phosphorus, soil pH, lime requirement and organic matter content, among others. After the tests, Demeter issues a report of the results to the farmer, with crop-specific fertiliser recommendations. They also follow up with an agronomist to help the farmer understand and implement the recommendations for optimal production. Since its inception in 2014, Demeter has become one of the primary providers of agricultural inputs and services in the country, helping farmers to enhance productivity and profitability (Demeter Ghana Limited 2025b).

While Demeter's model demonstrates the value of reliable soil analysis and advisory support, broader challenges remain within the soil testing landscape in the region. In soil testing, whether conducted in laboratories or under field conditions, it is crucial to apply appropriate methods and standards. Unfortunately, this is not always practised, particularly in developing countries. To tackle this problem, drawing from the experience of the Global Soil Laboratory Network (GLOSOLAN, FAO 2025a), Zambia has advanced in soil testing with the establishment of the Zambia Soil Laboratory Network (ZASOLAN, FAO 2025b). This initiative is a collaboration between the Zambian government, FAO's Global Soil Partnership (FAO 2025c) and Soil Mapping for Resilient Agrifood Systems (SoilFER, FAO 2025d) programme in

Central America and SSA. It aims to provide an interactive platform for soil laboratories to facilitate the sharing of best practices in capacity building and transfer of knowledge among participating laboratories. This is a good example of international collaboration drawing on past experience and government support, which are essential for success in improved agricultural production in SSA.

Despite the considerable success of the specific PA technologies highlighted earlier in SSA (e.g., PlantVillage), attempts to implement PA technologies in the region have not always been successful. For example, in a public-private partnership in Kenya involving local research institutes and Arable Labs, low-cost internet of things (IoT) devices (soil and weather monitoring devices) were installed on smallholder farms in piloted regions in the country to continuously track parameters such as soil temperature, moisture content and normalised difference vegetation index (NDVI) for precision irrigation and planting purposes. Data were sent to cloud dashboards and through short message service (SMS) alerts so that smallholder farmers, extension officers and researchers can make target irrigation, fertilisation and risk management decisions (Muriithi et al. 2024). While the pilot project proved beneficial, the project struggled beyond its initial sites, particularly in rural areas due to limited funds in extending public extension services to rural areas, lack of access to devices, unreliable internet for data transmission, low digital literacy levels among farmers, language barriers and incomprehensibility, among others (Fue et al. 2025; Muriithi et al. 2024).

Similarly, a digital advisory service (Tigo Kilimo) launched in Tanzania to provide real-time, location-specific advice on weather, agronomic practices and market price information for main markets in the country to smallholder farmers via basic phones, aiming to enable variable-rate input application, but failed to live up to expectations. Initial trials reached thousands of farmers in the country but failed to reach widespread adoption and sustained use. Notable reasons include the low willingness of farmers to pay for premium features, limited internet connectivity in remote areas and gender barriers (women had 15% lower internet usage compared to their male counterparts), among others (Gatsby Africa 2022). Based on the synthesis of the case studies reviewed, five key lessons emerge from the successes and failures of PA initiatives among smallholder farmers in SSA. These lessons are discussed below, while Table 1 presents a cross-case synthesis of the findings and their implications for future PA initiatives.

1. *Farmer-centred approaches and localisation of PA initiatives can drive sustained adoption*: The success stories, particularly those of PlantVillage and SWA, highlight the importance of farmer-centred approaches and localisation of PA initiatives to enhance adoption among smallholders in SSA. Both initiatives were designed with the farmer as the focal point: local training, demonstrations, simple mobile compatibility and interfaces, among others. As such, future interventions should consider a co-creation approach, design PA technologies with smallholders in the region from the onset, incorporate local knowledge and languages and establish peer networks to build capacity and adapt PA technologies to regional farming situations to ensure sustained adoption (e.g., Dittmer et al. 2024; Mhlanga 2024).
2. *Internet connectivity remains a challenge*: The failures of the IoT sensor pilots in Kenya and Tigo Kilimo in Tanzania underscore how unreliable internet connectivity and poor infrastructure, particularly in rural areas, prevent the widespread adoption of PA technologies among smallholders in the region (e.g., Fue et al. 2025; Choruma et al. 2024). In contrast, successes such as PlantVillage's offline AI diagnostics demonstrate that offline functionality is also important for PA adoption in SSA, particularly in remote rural areas where internet connectivity remains challenging. To improve the situation, offline PA tools should be encouraged in the region. Additionally, existing infrastructure, such as mobile network operators, should be leveraged for SMS alerts and data transmission, as these systems are generally well-developed in SSA, even in remote areas (e.g., Mothobi and Kebotsamang 2024).
3. *Access to finance is critical for adoption and sustainability*: High investment costs for PA technologies and farmers' unwillingness to pay for premium features condemned the initiative Tigo Kilimo, and the IoT sensors project also suffered a similar fate due to limited funding. However, SWA's flexible financing schemes and pay-as-you-go services led to sustained adoption of the promoted PA technologies among smallholders. Accordingly, for future PA projects to be successful among smallholders in SSA, flexible financing schemes such as micro-credits, pay-as-you-go services or bundled services with input suppliers should be considered to enhance adoption (e.g., Mapanje et al. 2023; Gatsby Africa 2022).
4. *Gender inclusivity enhances impact*: Women play a central role in agricultural production and development in SSA, yet they continue to face systemic barriers, such as limited digital literacy, restricted access to credit and land and persistent income inequality, that limit their ability to access and adopt new technologies (e.g., Asiseh et al. 2025; Olaoye et al. 2025; Akpa et al. 2024; Choruma et al. 2024). For example, women's lower access to mobile internet contributed to uneven uptake of digital services like Tigo Kilimo in Tanzania, whereas successful PA programmes like SWA reached 40% women through inclusivity and targeted approaches. Therefore, gender-inclusive design must be considered through tailored approaches in developing PA tools and technologies to enhance adoption among women in SSA (e.g., Ozor et al. 2025; Phiri et al. 2022).
5. *Integration of support services is critical for sustainability*: The failure of the IoT sensors project in Kenya beyond the pilot phase underscores that isolated PA deployments fail without support services. In contrast, the success stories of the PlantVillage, SWA and Demeter's PA soil testing highlight the importance of providing farmers with the necessary technical and advisory support to enhance the adoption and continued use of PA tools and technologies among smallholder farmers in SSA. Accordingly, it is necessary to bundle PA tools and technologies with a holistic support system, including training, installation, maintenance and possibly, market linkages to improve adoption

TABLE 1 | Cross-case synthesis of factors influencing the success and failure of PA initiatives in SSA and their implications for future initiatives.

Cross-case lesson	Evidence from successful cases	Evidence from unsuccessful cases	Implications for future PA initiatives
Farmer-centred design and localisation of technologies	PlantVillage, and SWA used local languages, demonstrations and farmer training, leading to sustained adoption	PA technologies designed without sufficient adaptation to local contexts experienced lower uptake	Co-design technologies with farmers, use local languages, demonstrations and peer learning networks to enhance uptake
Reliable internet infrastructure is essential	PlantVillage's offline functionality enabled use even in rural areas with poor connectivity	IoT sensor pilots and Tigo Kilimo were constrained by unreliable internet and network coverage	Develop offline-capable PA tools and leverage existing mobile networks for data transmission to enhance accessibility and expand reach
Access to finance is critical for adoption and sustainability	SWA's microloans and pay-as-you-go financing schemes improved adoption	Lack of finance contributed to the discontinuation of Tigo Kilimo and IoT sensor initiatives	Promote microcredit and flexible financing models, such as pay-as-you-go financing, bundled services, contract services and cooperative ownership, to enhance the uptake of PA technologies
Gender inclusivity enhances impact	SWA successfully reached approximately 40% of women through targeted approaches	Gender disparities in digital access reduced uptake of digital advisory services (Tigo Kilimo) in Tanzania	Design PA technologies and training programmes that specifically address barriers faced by women farmers to improve uptake among women in SSA
Integration of support services is critical for long-term sustainability	PlantVillage, SWA and Demeter combined technology with training and technical support	IoT sensor projects struggled after pilot funding ended because the necessary support systems were lacking	Integrate advisory services, maintenance, training and market linkages into PA deployment

Source: Authors' elaboration based on the case studies used for this review.

and the long-term sustainability of PA models in the SSA smallholder context (e.g., Nyaga et al. 2021).

3 | Data Management

PA relies on the availability of temporal and spatial variability data for efficient resource allocation. Previous studies have highlighted the importance of data for PA operations (e.g., Gobezie and Biswas 2023; Akhter and Sofi 2022; Huang et al. 2018; Castle et al. 2015). Data accuracy is important for the efficient application of resources and for optimal decision making. However, data collection may be challenging for farmers, especially smallholder farmers in developing countries due to technological and logistical constraints. As such, decision making may be compromised and farmers may not benefit from the full potential of adopting PA technologies in their farm operations.

Smallholder farmers in SSA face a number of specific challenges in managing data for PA. Limited digital literacy and technical skills among farmers hinder their ability to efficiently collect and interpret data (Mwangi and Kariuki 2015). Inadequate access to reliable internet connectivity and insufficient storage and processing capabilities for large datasets further complicate data management efforts (Wolfert et al. 2017). Also, the lack of affordable smart devices and sensors poses a significant barrier to data collection and analysis (Kamilaris et al. 2017). Additionally, concerns about data privacy and security may discourage farmers from fully embracing digital agriculture technologies (Ferrer Sapena et al. 2024). Integrating traditional farming knowledge with digital data also presents a challenge, as farmers may struggle to reconcile their longstanding practices with new technological approaches (Nyaga et al. 2021). While many of these challenges are prevalent globally, they may have an amplified effect for SSA smallholder farmers.

To address these challenges, several solutions have been suggested which include: (a) developing user-friendly mobile applications tailored for low-literacy areas to improve data accessibility and usability (Aker 2011); (b) implementing offline data collection and synchronisation methods to overcome connectivity issues (Beza et al. 2017); (c) establishing community-based data centres and shared equipment programmes to provide farmers with access to essential technology and storage capabilities (Deichmann et al. 2016), as well as providing training and capacity building in digital agriculture skills to empower farmers to effectively manage and utilise data (Tsan et al. 2019); (d) utilising low-cost, locally adaptable IoT devices for data collection to make PA more accessible to smallholder farmers (Nigussie et al. 2020), along with implementing blockchain technology for secure and transparent data management to address privacy and security concerns (Lin et al. 2017); and (e) creating partnerships between farmers, extension services and technology companies to facilitate knowledge transfer and support the adoption of data-driven agricultural practices (Klerkx et al. 2019).

In SSA, effective data management in PA is crucial (Chabilall et al. 2024). There are various data types in the management of PA. These include (a) soil data—pH, nutrient levels, moisture (Bekunda et al. 2010); (b) weather data—temperature, rainfall, solar radiation (Kibirige 2018); (c) crop data—yield, growth stage, health (Unganai and Kogan 1998); (d) equipment data—tractor usage, fuel consumption (Singh et al. 2020); and (e) financial data—costs, revenues (Sy and Tinker 2020). Data collection methods include sensors (e.g., for determining soil moisture, temperature) (Anderson et al. 2012), drones for aerial imaging and crop monitoring (Gokool et al. 2023) and the use of satellite imagery for crop health and yield prediction (Lungu et al. 2020). Others include mobile apps (farmer surveys, data entry) and automated weather stations. Data management tools commonly utilised in SSA include (a) Farm Management Information Systems (FMIS); (b) Geographic Information Systems (GIS); and (c) data analytics software (e.g., Tableau, Power BI), as well as cloud-based platforms (e.g., Google Cloud, AWS) and open-source platforms (e.g., OpenFarm, FarmOS).

Several digital data-management systems are emerging in SSA to address the specific challenges faced by smallholder farmers. In Ghana, platforms such as Agwise, Esoko and HingaSmart provide AI-enabled agronomic intelligence, market information, weather advisories and interoperable digital services that support farm-level decision-making. Other initiatives, including the Agriculture Innovation Data Hub (AIDH), FarmSense AI and Soil Hub, use digital tools for soil-health assessment, fertiliser recommendations and farm-data management. More broadly, DigiFarm Kenya offers an integrated digital agriculture platform that combines advisory services with market and financial information, while PlantVillage provides AI-based pest and disease diagnosis tailored to smallholder conditions. Open-source platforms such as farmOS offer low-cost options for farm-record management, and RiceAdvice delivers field-specific crop-management recommendations through a mobile application. Recent evidence from Nigeria indicates that the adoption of RiceAdvice is influenced by factors such as perceived usefulness, ease of use and access to extension support (Amoussohoui et al. 2024).

A developing case study, the Asasepa AI crop recommendations system, has been designed to help farmers in Ghana move towards PA principles and choose the best crops for their land based on soil nutrients. The system measures key elements such as nitrogen, phosphorus and potassium (NPK), all vital for plant growth and combines this information with past crop yields and local weather conditions. Using this data, deep learning models suggest the most suitable crops for each type of soil, helping farmers increase productivity while reducing environmental impacts. The project is using small, affordable sensors connected to simple computing devices to collect and process soil data. Tests show that the system correctly predicts the best crop options in most cases, matching or even surpassing traditional methods. Farmers could use these results to plan more effectively, reduce fertiliser waste and achieve better harvests. This approach provides an example of an important step towards PA and data-driven and sustainable agriculture. With further development, such as adding real-time weather and soil moisture information, the system could become an even more accurate and accessible tool to support farming decisions in different SSA regions.

The systems introduced here demonstrate how digital tools can help overcome constraints related to limited connectivity, low digital literacy, fragmented farm data and weak extension services, thereby improving the accessibility and effectiveness of PA for smallholder farmers in SSA. However, to implement such solutions, there is a need for a business model that encompasses valuing data capture and data privacy for smallholder farmers (Kaur et al. 2022).

4 | Agri-Entrepreneurs and the Economics of Precision Agriculture

Despite enormous potential benefits of PA technologies for farmers (e.g., Wang et al. 2023; Khanna et al. 2022), adoption rates remain low particularly among smallholder farmers in developing countries (Lowenberg-DeBoer and Erickson 2019). Farmers have on occasion adopted PA technologies for their farm operations, only to later discontinue their usage, citing reasons such as lack of profitability and other factors (Gabriel and Gandorfer 2023; Munz 2024). This occurs because farming is a business and farmers should only adopt and use PA technology if it is economically profitable (Lowenberg-DeBoer et al. 2021; Lowenberg-DeBoer 2019). Compared to small-scale farms, larger farms could implement PA in their farm operations due to, for example, their better financial position and larger economies of scale (Mizik 2023). However, farm holdings in SSA are generally small (e.g., Abay et al. 2023; Oumer et al. 2020; Berger et al. 2017) and the high cost of PA technologies may render PA intractable for farmers in the region. Previous studies have provided insights into the economics of PA for farmers (e.g., Lowenberg-DeBoer 2024, 2022, 2019; Lowenberg-DeBoer et al. 2021; Munz 2024; Koutsos and Menexes 2019). This section examines the evidence on monetary returns to PA in Africa and challenges to adoption.

Profitability of PA technology in the South African commercial agriculture sector has been documented with results similar to those found in Europe, North America and Australia. For example, Maine et al. (2010) used data from on-farm variable-rate technology (VRT) fertiliser trials on farms in the Free State to show that VRT profits varied from year to year, but overall VRT was slightly more profitable than uniform application. The Maine et al. (2010) study considered the cost of variable-rate fertiliser technology as well as changes in fertiliser costs. Based on an online survey of South African farmers, Truter et al. (2025) argued that adoption of PA technology is higher than previously believed and the main reason for adoption is to improve profitability. Forty-three percent of participants in Truter et al. (2025) survey responded that they had fully adopted PA technology and the main reason for that adoption was to improve productivity or economic performance. Over 50% responded that they had partially adopted PA technology. On-farm trials by Grain South Africa (Grain SA), University of Stellenbosch and the Bureau for Food and Agricultural Policy showed increased return over fertiliser costs from VRT fertiliser and seeding despite yield variability (Grain SA 2026). These trials were in nine maize fields in the Free State, Northwest, Gauteng and Mpumalanga. The fact that results in the South African commercial sector are similar to studies done in Europe, the Americas and Australia is not surprising because they are mechanised commercial farms, using mainly US and European technology, on many of the same crops. The challenge of showing benefits from PA technology on smallholder farms in other parts of Africa is greater.

Evidence on returns to more precise fertiliser application in Africa seems highly variable. Microdosing fertiliser is a site-specific farming practice in which farmers manually apply small amounts of fertiliser (e.g., 2–6 g per plant) to growing crops. Twomlow et al. (2010) provide evidence from over 1200 on-farm trials that low-tech fertiliser microdosing on maize, sorghum and millet in Zimbabwe reliably increases yields more than enough to cover the cost of fertiliser and application labour. Okebalama et al. (2017) review microdosing research in West Africa and conclude that it reliably covers cash costs but creates labour allocation challenges because it occurs during the seeding and weeding period and may lead to soil nutrient imbalances. Machines to precisely distribute microdose fertiliser are technically feasible but would substantially increase costs.

Mamman et al. (2025) did small plot precision fertilisation trials at two locations in Katsina State, Northwest Nigeria, in the 2023/2024 rainy season. The treatments were: (a) a control with no fertiliser; (b) organic fertiliser applied following typical farmer practices; (c) fertiliser at the recommended rate; and (d) fertiliser applied based on soil sensor readings. Partial budgeting showed that the recommended fertiliser rates provided the highest return over fertiliser costs. The net return to the soil sensor-based treatment would have been even further disadvantaged if soil sensor hardware, software and training costs had been deducted. The soil sensor-based fertiliser application provides higher yield and greater return over fertiliser cost than farmer practice at one location where rainfall and soil conditions were more favourable.

None of the available research considers the profitability on smallholder farms in Africa of the within-field variable rate technology that was introduced on commercial farms in South Africa in the early 2000s. Part of the challenge is the relatively small area of many African smallholder fields, which are often smaller than the grids or management zones used for VRT elsewhere in the world on larger fields.

While soil moisture sensors have been widely shown to improve yields and reduce irrigation water use on smallholder farms in Africa through precision irrigation scheduling, the financial feasibility of this technology is still in question. The Chameleon soil moisture sensor is one of the most widely tested in Africa, but in most cases, it is tested with donor-supplied technology (e.g., Chikankheni et al. 2025; Stirzaker and Driver 2025; Moyo et al. 2020; Stirzaker et al. 2017), making it difficult to assess farmers' ability to pay the full cost, including technology costs. Abebe et al. (2020) assessed farmers' willingness to pay (WTP) for Chameleon soil moisture sensing in Zimbabwe. They found that the farmers were willing to pay an amount, but not enough to cover the full cost of the sensors. WTP study participants often do not follow through on their stated willingness when faced with actual purchase decisions (Andorfer and Liebe 2015). Nonetheless, the Abebe et al. (2020) study is an indicator that many smallholders may face challenges in paying the full cost of the technology. Some researchers have argued that institutional innovation is required to enable sharing the cost of soil moisture sensing technology (Bjornlund et al. 2020). One of the economic facts of irrigation in Africa is that in most cases irrigation water fees are low or entirely absent, and when there are fees, often payment is not enforced, so water saving in itself often has little economic interest for farmers. The profitability of precision irrigation technology on smallholder farms in SSA often depends on reducing nutrient leaching, less salinity, lower pumping costs and increased yields.

Similarly, media and non-governmental organisations (NGOs) have provided glowing reports of the benefits of drone spraying in Africa (e.g., Further Africa 2023a, 2023b, 2023c; Kriel 2021; TechnoServe 2018), but research studies on the economic benefits have raised questions about whether farmers are willing to pay the full cost of drone application. For example, a study done by researchers from the University of Cape Coast, Ghana, on drone spraying for fall army worm in maize fields in three districts in Northern Ghana showed budgeted gross margins over variable costs for drone spraying was slightly better than for knapsack spraying (e.g., GHS 3281.32 (€531) vs. GHS 2344 (€379.35) in Nyankpala, one of the study districts) (Annor-Frempong and Akaba 2019). The variable costs in that study included the pesticide cost but did not include the drone application fee. In a survey of farmers who participated in drone spray field days, most expressed a WTP for drone spraying, but not the full €18.23 per hectare fee charged by the private company involved in the demonstrations. The company, Acaquahmeyer Drone Tech Ltd. (https://acquahmeyerdronetech.com/), was started by a Ghanaian entrepreneur with mostly their own capital (Ayemoba 2023), so the drone application fee may be a reasonable estimate of the true economic cost of supplying that service. The Acaquahmeyer fee is within the range of fees reported for the US and China, but much lower than drone application fees in the European Union (Maritan et al. 2025).

Because PA adoption in Africa is relatively recent, only a few studies have tried to estimate whole farm or aggregate returns to the technology. Yusuf and Akinola (2025) did a survey of a stratified random sample of 250 smallholder farmers in Oyo State, Southwest Nigeria. Econometric analysis shows that an index of PA adoption was a statistically significant predictor of higher net farm income per hectare. The PA index was constructed from data on adoption of GPS for field mapping, farm management software or apps, drone services for monitoring, soil testing and automated irrigation timers. Unfortunately, they do not explain how the PA index was created and do not provide disaggregated impacts by technology. Consequently, the Yusuf and Akinola (2025) study does not help us identify which PA technologies were more influential in creating higher farm income. Sarah et al. (2025) attempt to econometrically estimate national productivity impact from PA adoption in Nigeria during the period 1990 to 2023. They found a statistically significant increase in agricultural productivity linked to technology adoption during the period but failed to document the sources of data and how the technology adoption index was constructed.

Despite the potential economic benefits, most PA technologies have high upfront investment costs and recurring costs, making them prohibitively expensive for smallholders in SSA (e.g., Yusuf and Akinola 2025; Kwao et al. 2024; Bosompem 2021). Additionally, there are also human capital costs related to training and digital skills development to use these technologies (e.g., Kwao et al. 2024; McCarthy et al. 2023). These costs create economies of scale, making PA technologies more economically viable for larger farms, while the predominance of small and fragmented landholdings in SSA limits their financial feasibility for smallholders. In terms of adoption pathways, alternative financing models (e.g., Kariuki et al. 2020), including fee-based service provision, pay-as-you-go financing, cooperative ownership and bundling PA technologies with complementary services (e.g., input supply, extension services, credit, agricultural insurance), can help spread fixed costs across multiple farmers, reduce investment risks and overcome liquidity constraints. Such approaches are particularly relevant in the context of smallholders in SSA, where access to agricultural credit remains limited (e.g., Asiseh et al. 2025; Shuaibu and Nchake 2021), especially in rural areas, leaving many farmers unable to finance large capital investments. To date, robust evidence on the economics of PA for smallholder farmers in SSA remains limited (e.g., Annor-Frempong and Akaba 2019; Abebe et al. 2020; Twomlow et al. 2010; Okebalama et al. 2017; Mamman et al. 2025). Most economic evaluations of PA technologies have focused on medium and large-scale farms in developed countries, where economies of scale substantially enhance profitability. Consequently, rather than directly transferring these findings to SSA, greater emphasis should be placed on developing low-cost, locally adaptable PA technologies and service-based business models that reduce fixed investment costs and improve the financial feasibility of PA for smallholder farmers in the region.

5 | Integration of Precision Agriculture Into Curriculum and Training

PA has the ability to improve farm productivity and profitability (e.g., Wang et al. 2023; Parikoglou et al. 2022). Nonetheless, for this to be realised, especially by smallholder farmers in SSA, it is important for stakeholders to have the necessary awareness, knowledge and capacity to support PA. This could be achieved through the integration of PA into the educational curriculum of agricultural institutions in SSA, and by offering training programmes on PA to students, extension officers, farmers and researchers in the region. Currently, it is not clear whether the educational curriculum in SSA, particularly for agricultural students, has sufficient coverage of PA. In many African institutions, PA has not been sufficiently integrated into agricultural curricula, reflecting a knowledge gap between conventional farming methods and modern technological advancements. The few higher educational institutions integrating PA in their curriculum also lack most of the requisite competencies to transfer these skillsets to their students. In addition, challenges such as limited awareness and training and resource constraints limit integration (Njoroge et al. 2025), but opportunities for progress exist through strategic initiatives and international cooperation.

In this respect, the farm international mechanisation company, AGCO, attempted to address the education gap with a unique, fully funded 24-month programme for African graduates entitled AGCO Agribusiness Qualification (AAQ), which was hosted at Strathmore University in Nairobi, Kenya from 2018 to 2020 with technical content delivered by Harper Adams University (HAU), UK. This was open to participants from across Africa and course content focused on agri-tech, sustainability, farm mechanisation, farm business management and personal development. The programme was successful, with some of the initial cohort of 20 students employed directly by AGCO, whilst others pursued business and advisory opportunities within the sector. The AAQ course was modified for the second iteration between 2021 and 2023 and relocated to South Africa and hosted by the Gordon Institute of Business Science (GIBS), with technical content again delivered by HAU. The course was funded by the AGCO Agriculture Foundation, a private foundation initiated by AGCO in 2018 with a commitment to end hunger through sustainable agricultural development. There was an increased emphasis on agri-tech content within the curriculum, and graduates of the course were assimilated into technical and managerial positions.

Such initiatives highlight the critical role that education plays in strengthening Africa's agricultural transformation. There is a direct link between food security and the education of rural youth, as education can help improve farmers' livelihoods (FAO 2007). PA education offers potential to accelerate agricultural transformation in SSA. Integrating PA into existing agricultural training institutions will ultimately increase agricultural productivity and profitability, contributing to sustainable development through food security and increased farmer incomes. Systemic PA education is lacking in SSA. However, if PA education is strategically implemented, it could lead to increased enrolment, skills development and catalyse greater youth involvement in agriculture across SSA. Investments in PA skill training and education are likely to empower SSA's youth with new knowledge and sharpen their skills for highly paid jobs. Romanov et al. (2016) argue that PA enables farmers to observe, control and evaluate farm operations. However, global adoption rates are low, particularly in developing countries (Paustian and Theuvsen 2017). There is often a gap between the kind of training provided and the demands of the labour market in an evolving agricultural sector (Kalufya and Mwakajinga 2016). Therefore, PA education should be delivered in ways that will transfer the necessary skills and result in good employment outcomes. A wide range of PA technologies, such as GIS, GNSS technology, soil sampling tools, yield monitors, farm management applications, remote sensing tools and variable-rate application technologies are currently available (Robertson et al. 2012; Paustian and Theuvsen 2017). Thus, policymakers, local authorities and managers of educational institutions in SSA are expected to promote PA integration into the existing curriculum and create the enabling environments for PA growth at different levels of agricultural training institutions. The success of PA education in SSA is dependent on curriculum reform, targeted skill training and effective outreach, all of which require experienced faculty, adequate ICT and internet infrastructure and a supportive policy environment.

Another example of PA education and training that aims to build the technical knowledge and sharpen the skills of African graduates in PA is the Intra-Africa mobility project 'Capacity Building of African Young Scientists in Precision Agriculture Through Cross-Regional Academic Mobility for Enhanced Climate-Smart Agri-Food System (PATH)'. The PATH project, which started in January 2024, is a collaborative project among four African universities, including the University of Abomey Calavi, Benin, the University of Cape Coast, Ghana, the University of Rwanda, Rwanda and the University of Eswatini, Eswatini. The project also involves the University of Mohammed VI Polytechnic, Morocco, as an associate partner and the Institute of Agriculture of the Montpellier University as a European, technical partner. The programme targets the training of 12 PhD students, 32 Master's degree students, 10 staff and 10 interns from 2024 to 2028. The European Union has provided funding to support this Intra-Africa Academic Mobility to promote international learning mobility across the African continent as part of the Youth Mobility for Africa initiative within the Global Gateway Africa-Europe Investment Package.

Relatedly, the Mashal Papworth Fund provides educational opportunities for students from developing countries to gain the agricultural and horticultural skills needed to achieve a sustainable future for themselves and their communities through two scholarship programmes: (a) a one year master's degree in agriculture or horticulture and (b) a 10-week practical and experiential short course to empower change makers in rural communities, with both held at a UK-based university (Marshal Papworth 2025). The programme has been successful for nearly 20 years, with around 5 students per year on the master's degree course and 16 students on the 10-week course. Upon completion, Marshal Papworth scholarship students return to their home countries to apply their newly gained knowledge to benefit their communities through projects focused on improving local development practices leading to food security, sustainable agriculture and climate change adaptation. This typically includes teaching new skills to local farmers, initiating community projects, working in government or through NGOs.

6 | The Adoption of Precision Agriculture in Sub-Saharan Africa

The adoption of PA technologies has been discussed broadly in the literature (e.g., Le Hoang Nguyen et al. 2023; John et al. 2023; Lowenberg-DeBoer and Erickson 2019), and for small farms in particular (e.g., Fue et al. 2025; Aduramigba-Modupe and Oke 2024; Bashiru et al. 2024; Mizik 2023). These studies have highlighted several factors as enablers or barriers to PA adoption in smallholder farming systems. Key enablers include technological advancements, improved crop management practices, increased economic efficiency, supportive government policies and environmental sustainability, among others (e.g., Fue et al. 2025; Mizik 2023; Ofori and El-Gayar 2021). For example, a primary driver of PA adoption among smallholders in SSA is the proliferation of affordable digital tools, particularly mobile phones, in the region in recent decades and the growing availability of mobile-delivered PA technologies, which make PA viable even for poor resource-constrained farmers (e.g., Onyango et al. 2021; Nyaga et al. 2021). Mobile phone penetration in SSA reached nearly 47% of the population by the end of 2024 and is projected to grow steadily to about 53% in 2030 (GSMA 2025), making it possible for the delivery of mobile-based PA technologies and advisory services to farmers in the region.

However, these enabling factors are often constrained by numerous persistent barriers. These include farmer-specific socio-economic characteristics (e.g., farmer's age, farm size, annual income, digital literacy), costs of technologies, limited technical support for adoption (e.g., education and training), inadequate infrastructure (e.g., unreliable internet connectivity), data ownership, transparency and privacy concerns and government regulations (Mizik 2023; Ofori and El-Gayar 2021; Bosompem 2021). The principal among them is the high upfront costs of PA tools and technologies to smallholder farmers. Farmers in SSA are generally smallholders and may not have the financial capacity to purchase PA tools and technologies even if they promise future benefits. Inadequate capital, coupled with limited access to credit facilities and undeveloped financial markets (e.g., Asiseh et al. 2025; Shuaibu and Nchake 2021), particularly for farmers without adequate collateral to secure loans from formal institutions, makes it difficult for many farmers in the region to purchase and adopt PA technologies, which can cost several hundred or thousands of dollars. Until now, most commercial PA technologies have been designed and marketed for large and medium-scale mechanised farms, making them unsuitable for the heterogeneous and intercropped systems applied in smallholder contexts (Mizik 2023), particularly in SSA. This contextual misfit and lack of adaptability of PA technologies in smallholder settings not only limit the technical operability but also reduce the perceived usefulness in smallholder contexts. Thus, to enhance uptake of PA technologies among smallholders in SSA, manufacturers should prioritise the design and commercialisation of affordable, adaptable and highly cost-effective PA tools and technologies that address key production constraints for smallholders in the region.

Furthermore, beyond costs and the adaptability of PA technologies to smallholder settings in SSA, a key barrier that must be addressed is the lack of technical support for farmers, particularly in education and awareness creation, relating to training on equipment setup, operation and maintenance, as well as improving farmers' digital literacy skills (e.g., Bashiru et al. 2024; Mekonnen et al. 2024; Ofori and El-Gayar 2021; Bosompem 2021). This is necessary because it is established that knowledge and skills gaps are one of the primary barriers to the adoption of agricultural technologies among farmers in SSA (e.g., Bisheko and Rejikumar 2023; Mkenda et al. 2020). Many farmers in the region have limited access to education and awareness programmes that could help them understand the principles and potential of PA technologies. Even if farmers know of PA technologies, the lack of adequate training on equipment setup, calibration, operation and maintenance often leads to sub-optimal usage. Additionally, the low levels of digital literacy among farmers in the region may hinder their ability to interpret and make informed decisions from data generated by PA technologies (e.g., Fue et al. 2025). Accordingly, addressing these barriers through targeted capacity-building programmes will be critical to enhancing PA adoption among smallholders in SSA.

7 | Policy and Institutional Frameworks for Precision Agriculture Adoption in Sub-Saharan Africa

Evidence from SSA indicates that successful PA adoption is strongly associated with supportive government policies and institutional frameworks that strengthen digital infrastructure, extension services, agricultural data systems and access to finance. In Kenya, the Kenya Integrated Agricultural Management Information System (KIAMIS) represents a notable example of a government-led digital agriculture framework, establishing a national farmer registry linked to input subsidies, advisory services, financial products and market-access functions. By 2025, the platform had registered more than 6.5 million farmers, improving the targeting and delivery of agricultural support services while creating a foundation for site-specific, data-driven farm management. Likewise, Kenya's broader digital agriculture strategy has fostered an enabling ecosystem involving public agencies, research organisations, extension providers and private agri-tech firms, supporting the development and scaling of digital advisory, weather-information and decision-support tools (Njoroge et al. 2025). In Zambia, the Zambia Soil Laboratory Network (ZASOLAN), established through collaboration between the Government of Zambia and the Food and Agriculture Organization (FAO), has strengthened soil-testing capacity, laboratory standardisation and data quality, thereby supporting site-specific nutrient management.

Beyond these examples, evidence suggests that investments in the digital economy—including mobile connectivity, internet infrastructure and digital service platforms—provide the foundation upon which PA systems can be built. Countries such as Kenya have demonstrated how public investment in digital infrastructure and data systems can stimulate the development and uptake of PA technologies and services. At the continental level, initiatives supported by African Union institutions and the Comprehensive Africa Agriculture Development Programme (CAADP) have also helped create an enabling environment for data-driven agricultural innovation across SSA.

Additional examples from West Africa further highlight the importance of institutional reforms. In Benin, the establishment of a dedicated Directorate of Information Systems within the Ministry of Agriculture facilitated the implementation of drone-assisted land-mapping initiatives for climate-smart cashew production, reducing barriers to accessing precision mapping services among smallholders (Degila et al. 2023). Similarly, in Burkina Faso, government investments in digital governance and agricultural information systems provided the foundation for mobile-based extension services, market information systems and soil advisory networks that later supported digital agriculture initiatives (Degila et al. 2023). Evidence from Ghana also indicates that government-supported farmer-based organisations, improved access to rural credit and investments in localised agronomic training significantly increase both the likelihood and intensity of digital agricultural technology adoption among smallholder farmers (Miine et al. 2023).

These experiences demonstrate that successful PA adoption depends less on technology provision alone and more on the creation of an enabling ecosystem. Effective policy frameworks should therefore prioritise: (a) investment in digital public infrastructure, including broadband connectivity, farmer registries and interoperable agricultural data systems; (b) strengthening extension services and digital advisory platforms to improve farmers' technical capacity; (c) facilitating access to finance through innovative credit schemes and public–private partnerships; (d) supporting farmer-based organisations and cooperative structures that can aggregate demand and reduce adoption costs; and (e) promoting data governance standards that ensure data quality, interoperability, privacy and equitable access. By embedding PA within broader agricultural transformation and digitalisation strategies, governments can create the conditions necessary for widespread and inclusive adoption among smallholder farmers in SSA.

Despite these advances, significant policy gaps remain. Many SSA countries still lack comprehensive national PA strategies, resulting in fragmented implementation and weak coordination among government agencies, research institutions, extension systems and private-sector providers. Limited rural broadband coverage, inadequate digital infrastructure, insufficient historical soil and weather databases and weak data-governance frameworks continue to constrain the effectiveness of digital agriculture initiatives. In addition, public extension systems are often under-resourced and lack the technical expertise required to support farmers in the adoption and sustained use of PA technologies. Financial constraints also remain a major challenge, as many smallholders lack access to affordable credit and risk-management tools needed to invest in PA innovations. Gender disparities, low digital literacy and fragmented landholdings also continue to limit equitable access and reduce the economic viability of some technologies in smallholder settings. Addressing these institutional, infrastructural and socio-economic constraints will be essential if governments are to move beyond pilot projects and achieve the large-scale, sustainable adoption of PA across SSA.

8 | A Conceptual Framework for Enhancing PA Adoption Among Smallholder Farmers in SSA

Based on the evidence synthesised in this study, a conceptual framework is proposed to illustrate the key factors influencing PA adoption among smallholder farmers in SSA (Figure 1). The framework consists of four interconnected components: (a) barriers to PA adoption; (b) enabling strategies; (c) PA adoption; and (d) improved agricultural and socio-economic outcomes.

The first component highlights the major barriers limiting the adoption of PA technologies among smallholder farmers in SSA. The PA literature and the case studies reviewed consistently identify high upfront investment costs, limited access to finance, poor internet connectivity, inadequate digital skills, small farm sizes and gender-related inequalities, among others, as the principal constraints to PA adoption among smallholder farmers in SSA (e.g., Asiseh et al. 2025; Fue et al. 2025; Choruma et al. 2024; Bosompem 2021). These barriers reduce farmers' ability to access, utilise and sustain PA technologies despite their demonstrated productivity gains and environmental benefits.

The second component focuses on the enabling strategies required to overcome these barriers and facilitate PA technologies uptake. Evidence from the successful initiatives reviewed in this study indicates that farmer-centred approaches, localisation of technologies, innovative financing schemes, gender inclusivity, offline functionality and continuous technical support substantially enhance the accessibility, affordability and long-term sustainability of PA technologies (e.g., Kariuki et al. 2020; Dittmer et al. 2024; Mhlanga 2024; Nyaga et al. 2021). These complementary interventions reduce investment risks, strengthen

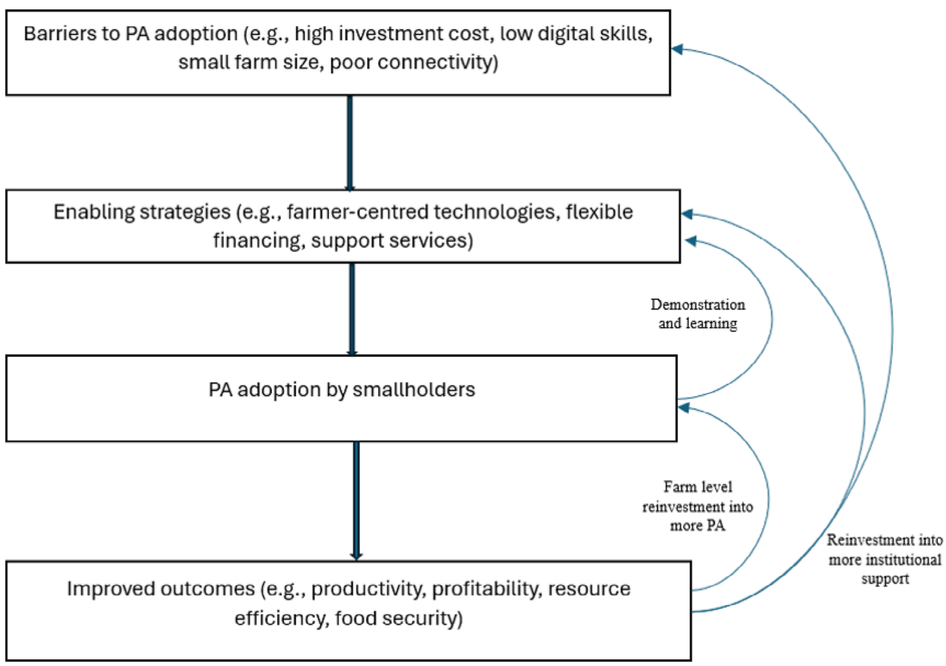

FIGURE 1 | Systems-based conceptual framework for improving precision agriculture adoption among smallholder farmers in SSA.

farmers' technical capacity, thereby improving PA adoption and its sustained use among smallholders.

The third component considered in Figure 1 represents the adoption of PA technologies by smallholder farmers. Once key barriers have been addressed through appropriate enabling strategies, farmers are more likely to adopt PA technologies. The case studies reviewed in this study show that adoption is influenced not only by the potential benefits of the proposed technology but also by the broader environment in which farmers operate. Consequently, creating an enabling environment for agricultural development is fundamental to achieving sustained PA adoption among smallholder farmers in SSA.

Finally, the fourth component focuses on the expected outcomes of successful PA adoption among smallholders in SSA. These outcomes occur at two interconnected levels. At the farm level, existing evidence suggests that the adoption of PA technologies can improve agricultural productivity, increase resource-use efficiency, enhance farm profitability and strengthen resilience to climate variability through more precise management of agricultural inputs (e.g., Aduramigba-Modupe and Oke 2024; Wang et al. 2023; Khanna et al. 2022; Koutsos and Menexes 2019). Collectively, these improvements can lead to broader development impacts, including improved food security among smallholder households, environmental sustainability and enhanced rural livelihoods in SSA. The framework also incorporates feedback loops. For example, improved farm productivity and profitability can encourage smallholders to reinvest in additional PA technologies, thereby stimulating continued adoption. Similarly, successful adoption and its wider development impacts can strengthen the enabling environment through learning and demonstrations, increased policy support (e.g., expanded extension services) and greater private-sector investment, thereby creating favourable conditions for sustained PA adoption among smallholders in the region.

The proposed conceptual framework synthesises the evidence reviewed and demonstrates that successful PA adoption among smallholder farmers in SSA goes beyond technological innovation. Rather, it requires addressing the economic, social and institutional barriers that constrain adoption while simultaneously creating the enabling conditions that allow farmers to realise the full benefits of PA technologies.

9 | Conclusion

PA holds enormous potential for smallholder farmers in SSA, where agriculture remains central to economic development, employing more than half of the adult population and contributing significantly to GDP. This paper has highlighted how PA is able to optimise resource use, enhance productivity and improve profitability in smallholder systems through tailored approaches, such as basic soil test kits, drip irrigation systems and mobile-based PA technologies. Despite challenges such as low adoption rates, high upfront costs, unreliable internet connectivity, limited digital literacy and inadequate training, evidence from successful initiatives such as PlantVillage, SWA and Demeter's soil-testing services, among others, demonstrates that when PA technologies are localised, inclusive and when supported by tailored training and financing schemes, smallholders can achieve substantial gains in input use efficiency, yield and strengthen climate resilience.

To fully realise these benefits, future initiatives should prioritise affordability, accessibility in remote areas (e.g., offline functionality) and capacity building. Co-creation of technologies with farmers, coupled with flexible financing approaches such as microloans and pay-as-you-go models, can make PA economically viable for smallholders in the region. Integrating PA into the agricultural education curriculum and extension systems will also create a supply of informed practitioners and farmers capable of sustaining adoption, while strengthening data management systems will be critical for long-term success.

Future research should focus on developing and evaluating affordable, locally adaptable PA technologies that address the heterogeneous production constraints faced by smallholder farmers in SSA. There is also a need to better understand how digital data-management systems, AI-enabled decision-support tools and emerging advisory platforms can improve farm-level decision-making while addressing challenges related to data governance, privacy, interoperability and digital inclusion. Additional evidence is required on the effectiveness of government policies, extension systems, public–private partnerships and innovative financing mechanisms in creating enabling environments for PA adoption under diverse institutional settings. To evaluate the profitability, scalability, environmental sustainability and distributional impacts of PA technologies across different farming systems, more rigorous economic assessments are needed. This includes understanding their effects on resource-use efficiency, climate resilience, gender inclusion and rural livelihoods.

In sum, scaling PA technologies among smallholder farmers in SSA can drive sustainable agricultural production, incentivise youth participation and enhance food security in the face of population growth and climate change. Achieving this, however, requires a multi-stakeholder effort linking researchers, farmers, agri-entrepreneurs, policymakers and development practitioners to develop a robust ecosystem for PA innovation and adoption. By prioritising localised designs, reliable infrastructure, gender inclusivity and sound data management, PA can become a transformative tool for smallholders in SSA.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

Data sharing is not applicable to this article as no datasets were generated or analysed during the current study.

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