



Precision Agriculture Technologies for Smallholder Farming Systems in Developing Countries: A Scoping Review of Opportunities, Limitations and Future Directions

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Abstract

Precision agriculture (PA) has emerged as a transformative approach for improving productivity, resource use efficiency, and environmental sustainability in modern farming systems. However, its adoption in developing countries where smallholder farmers dominate agricultural production remains limited and uneven. This scoping review critically examines the opportunities, constraints, and future prospects of precision agriculture in smallholder-dominated systems across Sub-Saharan Africa, South Asia, and Latin America. The paper synthesizes current evidence on the benefits of precision technologies, including remote sensing, Internet of Things (IoT) devices, artificial intelligence (AI)-driven advisory platforms, and unmanned aerial vehicles (UAVs), highlighting their potential to enhance yield optimization, reduce input waste, improve water management, and strengthen climate resilience. Despite these advantages, structural barriers such as high capital costs, weak digital infrastructure, fragmented landholdings, low technical literacy, inadequate extension services, and policy gaps significantly constrain adoption. Case studies from developing regions reveal that successful implementation often depends on institutional support, cooperative models, mobile-based platforms, and public-private partnerships. The review argues that transitioning from technology-centric approaches to system-oriented innovation frameworks is essential for inclusive and scalable implementation. Future directions should prioritize low-cost innovations, mobile-integrated precision tools, and shared service models for advanced technologies, AI-powered decision-support systems, and enabling policy environment. Ultimately, precision agriculture can contribute meaningfully to sustainable intensification and global food security, but its impact in developing countries will depend on context-specific design, equitable access mechanisms, and coordinated institutional support.

Keywords: Precision agriculture, Digital agriculture, Smallholder farming, Input optimization, Sustainable intensification, Technology adoption.

1.0 Introduction

Global food systems are under increasing pressure as the world population is projected to reach approximately 9.7 billion by 2050, necessitating substantial increases in agricultural productivity to meet rising food demand [1], [2]. Beyond population growth, changing dietary preferences, urbanization, and income expansion in developing economies are further intensifying demand for cereals, livestock products, and high-value crops [3]. However, expanding agricultural production is constrained by finite arable land, soil degradation, water scarcity, and the escalating impacts of climate change, making sustainable intensification an urgent global priority [4].

Smallholder farmers play a central role in addressing global food security challenges. Globally, farms smaller than two hectares account for the majority of farms and contribute significantly to food production in low- and middle-income countries [3]. In Sub-Saharan Africa and South Asia in particular, smallholder systems dominate agricultural landscapes and provide livelihoods for hundreds of millions of rural households [5]. Beyond food production, smallholders contribute to rural employment, poverty reduction, and local economic stability [6], [3]. Despite their importance, smallholder farming systems are often characterized by low productivity, limited mechanization, poor access to credit, and vulnerability to climatic variability, which collectively constrain their capacity to respond effectively to rising food demand [5], [7].

In recent years, precision agriculture has emerged as a transformative approach to improving agricultural efficiency and sustainability. Precision agriculture refers to the application of data-driven technologies, including remote sensing, Global Positioning Systems (GPS), Geographic Information Systems (GIS), Internet of Things (IoT) sensors, unmanned aerial vehicles (UAVs), and machine learning algorithms to enable site-specific crop and resource management [8]–[10]. By tailoring input application to spatial and temporal variability within fields, precision technologies can enhance input use efficiency, reduce waste, increase yields, and minimize environmental impacts such as nutrient runoff and greenhouse gas emissions [11], [12]. Furthermore, precision agriculture supports climate-smart farming practices by enabling adaptive decision-making under variable weather and soil conditions [13].

Despite these documented benefits, adoption of precision agriculture technologies remains highly uneven across regions. Uptake has been significantly higher in large-scale commercial farming systems in North America, Europe, and parts of Australia, where capital availability, digital infrastructure, and institutional support systems are more developed [14], [9]. In contrast, adoption among smallholder farmers in developing countries remains limited due to structural and socio-economic constraints [15]. High initial investment costs, fragmented landholdings, limited technical capacity, weak extension services, poor rural connectivity, and inadequate policy frameworks continue to hinder widespread implementation in low-resource settings [16], [15], [17]. This disparity has created a technological divide in global agriculture, where farmers in developed economies increasingly benefit from digital transformation while many smallholders remain excluded from precision innovations [18]. Without deliberate efforts to adapt precision agriculture technologies to the socio-economic realities of smallholder systems, the potential of digital agriculture to contribute to equitable food system transformation may remain unrealized [15], [17].

This review contributes to the growing body of knowledge by critically synthesizing existing evidence on the opportunities, limitations, and future directions of precision agriculture technologies for smallholder farming systems in developing countries. The review provides practical insights for researchers, policymakers, development agencies, and agricultural stakeholders on how precision agriculture can be adapted into affordable, inclusive, and context-specific solutions that enhance productivity, resource-use efficiency, and climate resilience among smallholder farmers. Therefore, a critical examination of the opportunities, limitations, and future pathways for precision agriculture in smallholder farming systems within developing countries is both timely and necessary.

2.0 Overview of Precision Agriculture Technologies

Precision agriculture encompasses a range of technologies that enable farmers to monitor, analyze, and manage crop production at fine spatial and temporal scales, thereby improving decision-making and resource use efficiency. One foundational technology is remote sensing, which uses satellite imagery, unmanned aerial vehicles (UAVs), and multispectral sensors to capture data on crop health, soil properties, and field variability. Remote sensing allows farmers to detect stress, nutrient deficiencies, and pest outbreaks early, leading to more targeted interventions and optimized field operations [19]. Integrating remote sensing data with Geographic Information Systems (GIS) supports site-specific crop management, enabling precise input application and reducing waste [19].

Internet of Things (IoT) sensors form another critical component of precision agriculture. These devices, deployed in fields or on equipment, continuously collect data on soil moisture, temperature, nutrient levels, and microclimatic conditions [20]. When connected via IoT networks, sensor data can be monitored in real time, allowing farmers to adjust irrigation, fertilization, and pest management practices according to actual crop and environmental conditions rather than fixed schedules [21]. It was reported by Kapari *et al.* [20] that IoT-integrated systems can significantly increase yields and water use efficiency by informing sorghum irrigation timing and nutrient supply decisions more accurately than traditional methods.

Artificial intelligence (AI)-based decision support systems are also transforming farm management by analyzing large volumes of agricultural data to generate predictive insights. AI algorithms can integrate remote sensing imagery, weather forecasts, and sensor data to forecast crop performance, optimize input applications, and recommend adaptive strategies for pest and disease control [22]. For example, machine learning models have demonstrated strong predictive capacity in yield forecasting and drought monitoring, which can enhance farmers' resilience to climate variability by enabling proactive planning [22].

Complementing these technologies, farm management software platforms synthesize data from remote sensors, IoT devices, and AI analytics into user-friendly dashboards that support planning, record-keeping, and decision-making. These platforms help farmers organize field operations, track inputs and outputs, and evaluate the economic and environmental outcomes of different management strategies [19]. By combining real-time data with historical trends, farm management software enhances strategic planning and ensures that precision agriculture technologies are actionable at the field level [19].

3.0 Opportunities for Smallholder Farmers

Precision agriculture presents substantial opportunities to improve productivity and livelihoods for smallholder farmers, especially in developing countries where resource constraints and climate variability pose persistent challenges. One of the most significant advantages is the potential for yield increases. Technologies such as remote sensing and IoT-enabled irrigation have been shown to improve crop yields by enabling targeted nutrient management and timely agronomic interventions based on real-time field data [19], [23]. By addressing spatial heterogeneity within fields, these tools help smallholders maximize output per unit area without proportionally increasing input use. In addition to yields, precision agriculture offers pathways for input cost reduction, which can directly enhance the profitability of small farms. Variable rate application systems, informed by soil and crop data, ensure that fertilizers, water, and pesticides are applied only where needed and in the right amounts [19]. Such precision reduces over-application and waste, helping farmers save on costly inputs while maintaining or

improving productivity. Lower input costs are especially valuable for smallholders who often operate with very thin profit margins and limited access to credit.

Water efficiency represents another major benefit of precision agriculture. Sensor-based irrigation systems and remote sensing-guided water management allow farmers to optimize water distribution based on actual soil moisture and crop needs rather than fixed schedules [20]. In regions facing water scarcity, such systems can dramatically reduce water use, enhance drought resilience, and support sustainable cropping practices [18]. By improving water use efficiency, smallholders can maintain productivity even under erratic rainfall patterns and prolonged dry spells.

Precision agriculture also contributes to climate resilience by supporting adaptive decision-making under changing environmental conditions. AI-based models and predictive analytics can forecast weather anomalies, pest outbreaks, and crop stress, enabling farmers to adjust their practices proactively [19], [22]. This capability enhances smallholder capacity to withstand climate shocks and reduces vulnerability to yield losses driven by extreme weather events. Precision agriculture fosters environmental protection by minimizing the ecological footprint of farming. By optimizing nutrient and water application and enabling precise pest management, these technologies reduce chemical runoff, soil degradation, and greenhouse gas emissions [19], [20]. Sustainable intensification through precision tools therefore aligns agricultural productivity with environmental stewardship, helping smallholder systems contribute to broader sustainability goals [24].

4.0 Limitations and Constraints

Despite its potential, the adoption of precision agriculture in smallholder farming systems is constrained by several interconnected challenges. A primary limitation is the high capital cost associated with acquiring precision technologies such as sensors, drones, and advanced software systems. These technologies often require significant upfront investment, making them inaccessible to many smallholders with limited financial capacity [9], [15].

Another major constraint is poor digital and internet infrastructure in rural areas of developing countries. Precision agriculture technologies often rely on real-time data transmission, cloud computing, and connectivity, which are hindered by unreliable or nonexistent internet access [17]. This infrastructural gap significantly limits the effectiveness and scalability of digital farming solutions.

The effectiveness of precision agriculture also depends on strong knowledge dissemination systems; however, weak agricultural extension services in many developing countries hinder technology transfer. Extension systems often lack the resources, training, and coverage required to support farmers in adopting and utilizing complex technologies [15]. This results in low awareness and limited practical application at the farm level.

Closely related is the issue of low technical literacy among smallholder farmers. Many precision agriculture tools require data interpretation and technical understanding, which may not be readily available among rural farming communities [10]. Without adequate training and capacity building, farmers may struggle to utilize these technologies effectively.

Policy and institutional gaps further constrain adoption. In many developing countries, there is a lack of clear policy frameworks supporting digital agriculture, including limited subsidies, weak regulatory systems, and insufficient investment in rural innovation [17]. These gaps reduce incentives for both farmers and private sector actors to invest in precision agriculture.

Additionally, fragmented landholdings, which are typical of smallholder systems, reduce the economic viability of precision technologies. Small and scattered plots limit the efficiency of technologies designed for large-scale, uniform fields, thereby increasing per-unit costs and reducing returns on investment [3].

5.0 Case Studies from Developing Countries

To illustrate how precision agriculture technologies are being explored in different regions, the following examples summarize research and implementation efforts in Sub-Saharan Africa, South Asia, and Latin America.

Sub-Saharan Africa

In Sub-Saharan Africa (SSA), precision agriculture adoption remains relatively limited but is gradually emerging in pilot projects and research initiatives. A systematic review of precision agriculture in SSA noted that sensor-based approaches for nutrient and water management, as well as satellite imagery and GIS tools for site-specific management, have been tested under local conditions and show promise for improving resource use efficiency [25]. However, most of these technologies are still at the experimental stage, with only a few applications reaching commercial scale, especially in South Africa, Nigeria, and Kenya [25]. These early cases highlight the potential of precision tools to optimize input use without requiring additional resources, a key factor in smallholder contexts, but also underscore the need for scaling and adaptation to local socio-economic conditions. In some SSA countries, initiatives are already deploying mobile-based advisory platforms to bridge information gaps. For example, personalized mobile applications such as Farm Connect and M-Shamba are being used to deliver

agronomic recommendations and market information to smallholder farmers, enhancing their decision-making capacity even where traditional precision technologies are absent or under-utilized [17].

South Asia

In South Asia, precision agriculture applications are similarly emerging through targeted case studies and regional initiatives. For example, multi-site studies of precision irrigation adoption among small-scale rice farmers in Indonesia demonstrated that sensor-based irrigation systems combined with drone-assisted land management can improve water efficiency by up to 27% and reduce labour costs, illustrating tangible benefits when technologies are combined with supportive extension services [15]. Although adoption remains nascent, these types of studies show clear benefits and provide policymakers with evidence for scaling appropriate technologies.

In India, adoption of precision farming tools remains below 10% in many areas due to persistent cost, educational, and infrastructure constraints, despite evidence of increased productivity and input optimization where technologies are deployed [13].

Latin America

Latin America presents a mixed but increasingly promising landscape for precision agriculture adoption among smallholders. Countries such as Brazil have reported moderate levels of precision farming application, particularly in crops such as soybeans where remote sensing and variable rate technology (VRT) have been used to optimize planting strategies and increase yields [26]. While these technologies are often more prevalent in larger farms, smaller farms in regions of Brazil and Mexico are increasingly accessing remote sensing tools and mobile advisory platforms to inform nutrient and water management, demonstrating blended adoption pathways that bypass some high-cost barriers [18].

Across these regions, case studies consistently show multiple benefits, including improved efficiency, better resource use, and enhanced decision-making when precision tools are effectively integrated with local contexts and support systems [9]. However, they also underscore the importance of context-specific adaptation, affordable delivery models, and institutional support to ensure that the benefits of precision agriculture are equitably accessible to smallholder farmers in developing countries.

6.0 Future Directions

Despite increasing recognition of the potential of precision agriculture in developing countries, adoption among smallholder farmers remains limited due to persistent structural, economic, and institutional barriers [15], [17]. Future progress therefore requires targeted strategies that enhance affordability, accessibility, and institutional support within smallholder contexts.

6.1 Low-Cost Innovations

The development of low-cost and scalable precision technologies is central to expanding adoption among smallholders. High-end sensor networks, UAV systems, and proprietary software platforms often exceed the financial capacity of small-scale farmers [9]. Research increasingly emphasizes frugal innovation approaches that prioritize simplified hardware, open-source software, and modular systems adaptable to small plots [17]. Locally manufactured sensors and region-specific digital tools may significantly reduce investment barriers while maintaining functionality [15]. Moreover, incremental adoption models where farmers integrate basic technologies before transitioning to more advanced systems have been suggested as more realistic pathways for low-income contexts [13].

6.2 Mobile-Based Precision Tools

The rapid expansion of smartphone penetration in developing regions presents an opportunity to deliver precision agriculture services without heavy capital investments in machinery [18]. Mobile-based platforms can integrate satellite imagery, weather forecasts, and soil analytics into user-friendly advisory systems that provide real-time, site-specific recommendations [10]. Such tools reduce complexity by translating data into actionable insights rather than requiring farmers to interpret raw datasets. Evidence suggests that digital advisory platforms improve decision-making efficiency and input management when designed with user-centered interfaces and local language adaptation [15]. Future research should emphasize offline capabilities and simplified dashboards to address connectivity challenges in rural regions.

6.3 Cooperative and Shared Drone Services

Unmanned aerial vehicles (UAVs) offer significant potential for crop monitoring, pest detection, and precision spraying; however, individual ownership remains economically prohibitive for most smallholders [9]. Cooperative ownership models and service-provider systems have been proposed as viable alternatives, enabling farmers to access drone services without bearing full capital costs [17].

Shared-service frameworks leverage economies of scale and distribute operational costs across farmer groups, improving feasibility within fragmented landholding systems. Institutional support, training programs, and regulatory clarity are essential to ensure safety, efficiency, and long-term sustainability [13].

6.4 AI-Powered Advisory Platforms

Artificial intelligence (AI) and machine learning applications are increasingly central to the evolution of precision agriculture. AI-driven decision-support systems can synthesize remote sensing data, weather forecasts, and historical yield records to generate predictive recommendations tailored to specific farm conditions [10]. Such systems enhance adaptive capacity under climate variability by providing early warnings for drought, disease outbreaks, and nutrient deficiencies [9].

However, concerns regarding data governance, algorithm transparency, and digital exclusion must be addressed to ensure equitable access and trust among smallholder communities [18]. Future research should prioritize explainable AI models and participatory data integration approaches that incorporate farmer knowledge.

6.5 Public–Private Partnerships

Scaling precision agriculture in developing countries will require coordinated collaboration between governments, private technology firms, research institutions, and farmer organizations [17]. Public–private partnerships (PPPs) can mobilize investment in rural digital infrastructure, strengthen extension services, and provide financial incentives that reduce adoption risk [15].

Governments play a critical role in establishing regulatory frameworks, investing in broadband infrastructure, and supporting innovation ecosystems, while private actors contribute technological expertise and market-based scalability [13]. Inclusive PPP models that prioritize smallholder participation and affordability are necessary to prevent the deepening of digital divides. Collectively, these future directions emphasize the need for systemic transformation that integrates technological innovation with institutional reform, farmer capacity building, and inclusive policy design.

7.0 Conclusion

Precision agriculture technologies present substantial opportunities for enhancing productivity, input efficiency, and environmental sustainability within smallholder farming systems in developing countries [9]. Tools such as remote sensing, IoT sensors, AI-based analytics, and farm management software enable site-specific resource management that aligns with the objectives of sustainable intensification and climate-smart agriculture [13].

However, adoption remains constrained by high capital costs, inadequate infrastructure, limited technical capacity, fragmented landholdings, and weak policy support systems [15], [17]. These barriers underscore the reality that technological innovation alone is insufficient; enabling environments and institutional frameworks are equally critical for successful integration.

Future efforts must therefore prioritize affordable and scalable innovation pathways, mobile-centered delivery systems, cooperative service models, AI-enabled advisory platforms, and robust public–private partnerships. By aligning technological development with socio-economic realities and inclusive governance mechanisms, precision agriculture can contribute meaningfully to equitable food system transformation in developing countries.

Practically, this review provides policymakers, development agencies, researchers, and agricultural stakeholders with evidence-based insight for designing cost-effective, inclusive, and context-specific precision agriculture interventions that can improve smallholder productivity, resource-use efficiency, and climate resilience. Ultimately, realizing the transformative potential of precision agriculture for smallholders will depend on interdisciplinary collaboration among engineers, agronomists, policymakers, and rural communities to ensure that innovation translates into accessible, scalable, and sustainable solutions.

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