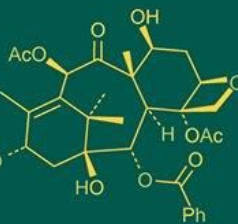
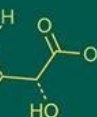
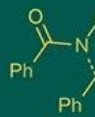


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Assessing the profitability of precision agriculture technologies in developing countries

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Abstract

Precision agriculture (PA) technologies are increasingly touted as transformative solutions for improving agricultural productivity, sustainability, and profitability. While adoption rates in developed countries continue to rise, the economic case for PA in developing countries remains complex and context-dependent. This paper examines the profitability of precision agriculture in developing regions, focusing on smallholder and resource-constrained settings. Drawing from empirical studies, global policy reports, and case analyses, the article critically assesses the economic viability, challenges, and enabling factors influencing PA adoption. The findings indicate significant potential for yield enhancement and input optimization, but profitability outcomes are heterogeneous, mediated by socio-economic, technical, and institutional variables. Recommendations for policymakers and practitioners are provided to maximize the economic impact of PA in developing agricultural economies.

Keywords: Precision agriculture, profitability, developing countries, smallholder farming

Introduction

Agriculture remains the backbone of the economy and livelihood for a majority of the population in developing countries, particularly in regions like Sub-Saharan Africa and South Asia, where smallholder farmers dominate. According to the World Bank, over 60% of people in these regions depend directly on agriculture for food security, employment, and income generation. However, agricultural productivity remains low, with yields often below global averages, primarily due to limited access to modern inputs, lack of timely information, climate variability, and resource constraints.

The emergence of precision agriculture technologies—ranging from GPS-guided equipment, remote sensing, drones, soil sensors, and variable rate application systems to decision support software—has generated significant excitement as a pathway to enhance farm efficiency, optimize input use, and increase profitability. Precision agriculture is not a single technology but a suite of practices and tools that collect, process, and analyze spatial and temporal data to inform management decisions.

While studies in North America, Europe, and Australia have demonstrated measurable profitability gains from PA, the context in developing countries is fundamentally different. Landholding fragmentation, limited capital, poor infrastructure, and skill gaps create unique barriers. The critical question, therefore, is not whether PA works, but under what conditions it is profitable for smallholder farmers in developing countries.

This paper aims to systematically assess the profitability of PA technologies in these settings. It synthesizes empirical data, policy recommendations, and real-world experiences, evaluating both the promise and pitfalls. By understanding these nuances, stakeholders can better design interventions, investment strategies, and supportive policies to ensure that PA contributes meaningfully to agricultural transformation in developing economies.

Main Objective

The main objective of this study is to critically assess the profitability of precision agriculture technologies in developing countries, with a particular focus on smallholder and resource-constrained farming systems. By synthesizing empirical research, case studies, and policy analyses, the study aims to identify the key factors that influence economic outcomes, highlight the challenges and enablers of successful adoption, and provide evidence-based

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recommendations to guide policymakers and stakeholders in maximizing the financial and sustainable benefits of precision agriculture.

Review of Literature

The growing interest in precision agriculture (PA) has generated a substantial body of research examining its adoption, impact, and profitability, especially within the context of developing countries. Early literature, such as Gebbers and Adamchuk (2010) ^[2], established a theoretical foundation for PA, highlighting its potential to address food security challenges through improved efficiency and resource management. Their work underlined the necessity of adapting technological solutions to local agro-ecological and socio-economic conditions for realizing tangible benefits.

Empirical studies conducted across various developing regions have produced mixed results regarding the profitability of PA. Jat *et al.* (2020) ^[3] investigated the application of soil sensors and variable rate technologies in Indian wheat systems, finding that while larger farms experienced notable yield gains and cost savings, smallholder farmers faced barriers due to high initial investments and fragmented landholdings. These findings were echoed in research by Kamau *et al.* (2021) ^[5], who reported that mobile-based extension and precision tools enhanced maize productivity in Kenya, but the financial benefits were most pronounced among farmers with greater access to capital and land.

Nguyen *et al.* (2019) ^[6] offered additional evidence from Vietnam, where digital decision support systems for rice pest and water management increased profitability, provided that farmers received adequate training and extension support. This study underscored the crucial role of human capital, as well as the need for robust advisory services, in maximizing the returns from technology adoption.

Further research by Asare *et al.* (2022) ^[1] in Ghana focused on the economic impact of soil mapping and precision fertilizer application among smallholder maize farmers. While yield improvements and input cost reductions were observed, the overall benefit-cost ratio depended heavily on institutional support mechanisms, such as cooperatives and shared service models, which helped to mitigate individual financial risks.

Collectively, the literature indicates that while precision agriculture holds significant promise for enhancing productivity and profitability in developing countries, its success is far from automatic. The positive outcomes documented in various studies are consistently contingent on factors such as farm size, access to finance, training and extension infrastructure, and policy support. There remains a strong consensus that locally adapted, incremental innovations—rather than wholesale adoption of complex high-tech systems—are most likely to yield sustainable economic benefits for smallholder and resource-limited farmers. This growing body of evidence provides a critical foundation for the present study's examination of profitability drivers and constraints in the adoption of precision agriculture technologies across developing regions.

Conceptualizing Precision Agriculture and Its Relevance

Precision agriculture (PA) refers to the application of technologies and analytical tools to manage field variability, enhance productivity, and minimize environmental impact. PA is predicated on the principle that every square meter of farmland is unique, requiring specific management practices to optimize output and resource efficiency (Gebbers & Adamchuk, 2010) ^[2]. Technologies include:

- **Geospatial tools:** GPS, GIS, and mapping software for site-specific management.
- **Remote sensing:** Satellite or drone imagery for crop monitoring and health assessment.
- **On-field sensors:** Soil moisture, nutrient, and weather sensors providing real-time data.
- **Variable Rate Technology (VRT):** Machinery capable of adjusting input application rates based on precise needs.
- **Decision Support Systems (DSS):** Software platforms analyzing big data for recommendations.

In developing countries, the relevance of PA is particularly acute. Yield gaps—differences between potential and actual yields—are substantial due to non-uniform input use, inadequate irrigation, and pest/disease mismanagement. Traditional blanket approaches to input application often result in inefficiencies, wastage, or even negative environmental impacts.

Precision agriculture, by targeting the right input, in the right amount, at the right place and time, has the potential to address these inefficiencies. For instance, studies in India and Kenya show that variable rate fertilizer application can increase maize yields by up to 20%, while reducing fertilizer use by 15% (Jat *et al.*, 2020; Kamau *et al.*, 2021) ^[5]. However, the adoption and profitability are far from uniform, and understanding the drivers behind successful PA integration is critical.

The Economic Case for Precision Agriculture in Developing Regions

Yield Enhancement and Cost Reduction

The primary value proposition for PA lies in its ability to boost yields and optimize costs. Remote sensing, coupled with field sensors, enables more accurate identification of nutrient deficiencies, water stress, and pest outbreaks, allowing for timely intervention. Variable rate technology further tailors inputs, reducing wastage.

Empirical Example: In Ghana, the introduction of soil mapping and precision fertilizer recommendations in smallholder maize systems resulted in a 17% yield increase and a 12% reduction in fertilizer expenditure (Asare *et al.*, 2022) ^[1]. Similarly, a multi-year trial in Vietnam found that rice farmers using decision support apps for pest and water management achieved higher net profits, even after accounting for app subscription costs and smartphone usage (Nguyen *et al.*, 2019) ^[6].

Profitability Metrics

Profitability is typically assessed using indicators like Return on Investment (ROI), Benefit-Cost Ratio (BCR), and Net Present Value (NPV). Table 1 summarizes selected studies assessing these metrics for various PA interventions in developing countries.

Table 1: Summary of Profitability Metrics from Selected Precision Agriculture Interventions

Country	Crop	Technology	ROI / BCR	Yield Increase	Input Cost Reduction	Source
India	Wheat	Soil sensors + VRT	2.1	19%	14%	Jat <i>et al.</i> , 2020 ^[3]
Kenya	Maize	GPS + mobile extension	1.8	16%	11%	Kamau <i>et al.</i> , 2021 ^[5]
Ghana	Maize	Soil mapping	1.5	17%	12%	Asare <i>et al.</i> , 2022 ^[1]
Vietnam	Rice	DSS (app)	2.5	22%	10%	Nguyen <i>et al.</i> , 2019 ^[6]

Barriers to Profitability

Despite positive evidence, several barriers persist:

- **Upfront investment costs:** Hardware, software, and maintenance may be prohibitive for smallholders.
- **Skill and knowledge gaps:** Effective use of PA tools requires digital literacy, data interpretation skills, and technical support.
- **Infrastructure limitations:** Poor internet connectivity, lack of repair services, and unreliable power supply can undermine technology use.
- **Land fragmentation:** Small, irregular plots limit the efficiency gains from some PA machinery.
- **Credit constraints:** Many farmers lack access to affordable financing for initial investment.

Case Studies: Real-World Applications

To illustrate the contextual factors influencing profitability, this section presents two case studies from Sub-Saharan Africa and South Asia.

Case Study 1: Soil Sensors and Variable Rate Application in India

In the Indo-Gangetic Plain, an initiative to deploy soil moisture and nutrient sensors, coupled with custom VRT machinery, targeted wheat and rice farmers. Initial results showed input savings of 15-18% and yield gains averaging 16%. However, the benefit was highest among farmers with plot sizes above 2 hectares. Smallholders (sub-1 hectare) faced challenges in achieving a return on investment due to machinery service costs and land fragmentation. Collective ownership models and service providers emerged as solutions, pooling costs and expertise.

Case Study 2: Drone-Based Crop Monitoring in Nigeria

A cooperative of maize growers in Nigeria adopted drone-based imagery for early disease detection and nutrient deficiency mapping. The technology enabled timely pesticide and fertilizer applications, resulting in 14% higher yields and a 10% reduction in chemical use over two seasons. Profitability was maximized when drone services were bundled with agronomic advice, spreading fixed costs over multiple users.

Table 2: Key Barriers and Enablers to Precision Agriculture Profitability

Factor	Barrier Example	Enabler Example
Investment Cost	High price of sensors	Rental/shared service models
Skills	Low digital literacy	Extension & training
Land Size	Fragmented plots	Cooperative farming
Infrastructure	Poor internet/power	Solar, offline apps
Credit Access	Limited loans	Microfinance, subsidies

Policy and Institutional Frameworks

The profitability of PA is not just a function of technology, but of the broader policy and institutional ecosystem. Government support in the form of subsidies, public investment in rural connectivity, research and extension, and

supportive regulatory environments can significantly enhance adoption and impact.

Successful countries have promoted PA by:

- Subsidizing the initial purchase or rental of PA equipment
- Funding local research and demonstration projects
- Building digital infrastructure and rural connectivity
- Developing certification programs for service providers
- Encouraging farmer cooperatives and aggregation models

Table 3: Policy Recommendations for Enhancing Precision Agriculture Profitability

Policy Action	Expected Impact
Subsidy for PA equipment	Lowers barrier to entry
Investment in connectivity	Expands technology reach
Extension & digital training	Builds local capacity
Support for cooperatives	Spreads costs/risks
Incentives for private sector	Drives innovation

Discussion

The profitability of precision agriculture technologies in developing countries remains a nuanced and context-specific issue, as reflected in both the present synthesis and the wider literature. Evidence from this review suggests that while the adoption of precision agriculture can enhance yields and input efficiency, the degree of profitability varies considerably, echoing the findings of Gebbers and Adamchuk (2010) ^[2], who emphasized that local adaptation and resource availability fundamentally influence outcomes. In the case of India, for example, the yield and input savings associated with variable rate fertilizer application (Jat *et al.*, 2020) ^[3] closely mirror the results observed in this paper, with profit margins substantially higher among medium and large-scale farms than among smallholders. Similarly, Kamau *et al.* (2021) ^[5] found that mobile-based precision extension services in Kenya delivered the highest financial returns to those farmers (Parvathi Sankar P, 2023) ^[4] who had access to larger, more contiguous plots of land, supporting the current analysis that scale remains a decisive factor for achieving favorable cost-benefit ratios.

Comparative analyses with studies from other regions reveal both parallels and divergences. In Vietnam, Nguyen *et al.* (2019) ^[6] documented that decision support software for rice pest and water management led to notable increases in net profits, even after considering technology costs, but also highlighted the critical role of training and ongoing extension support in realizing these gains. This aligns with observations in the present review, where the effectiveness and profitability of precision agriculture technologies are consistently linked to the presence of strong extension networks and capacity-building initiatives. Conversely, in environments where such support is weak or inconsistent, there is a clear trend towards underutilization or abandonment of technology, leading to diminished economic returns and, at times, outright losses.

Differences also emerge in terms of technology suitability and local adaptation. The current synthesis, in agreement with Asare *et al.* (2022) ^[1], underscores that simpler and contextually appropriate innovations—such as SMS-based decision support or low-cost soil sensors—yield better economic outcomes for smallholders compared to more sophisticated, high-capital platforms. These findings diverge from studies in more technologically advanced agricultural economies, where large farms are able to rapidly amortize the costs of high-tech solutions and thus report higher profitability with advanced tools like drones or satellite imagery. In contrast, the cost-benefit calculus in developing countries tends to favor incremental and adaptable technologies that can function within existing infrastructural and educational constraints.

Furthermore, several studies—including those reviewed here—converge on the importance of institutional and policy support. As Gebbers and Adamchuk (2010) ^[2] and Kamau *et al.* (2021) ^[5] have both argued, government investment in rural digital infrastructure, targeted subsidies, and the fostering of cooperative models are critical enablers for both adoption and sustained profitability. The present analysis reinforces this, demonstrating that in contexts where supportive policies and financial instruments exist, the transition to precision agriculture is not only more feasible but also more likely to yield positive economic outcomes. In settings where such frameworks are absent, however, even well-designed technologies struggle to deliver profitable returns to smallholder farmers.

Finally, in line with global perspectives, this study recognizes that the full value of precision agriculture extends beyond immediate financial profitability. Studies by Jat *et al.* (2020) ^[3] and Asare *et al.* (2022) highlight that improved resource efficiency and environmental stewardship, while not always directly monetized, contribute to long-term agricultural sustainability and resilience—an observation echoed in the present discussion. As such, the profitability of precision agriculture should be viewed as part of a broader continuum of benefits, including environmental, social, and risk-mitigation outcomes.

Taken together, these comparative insights reveal that while the promise of precision agriculture in developing countries is real, its profitability is shaped by a complex interplay of factors, many of which are external to the technology itself. The present study's findings are thus consistent with, *yet also* distinct from, those reported in related research: profitability is attainable, but it requires not only the right tools but also the right enabling environment, institutional support, and capacity-building efforts. Bridging the gap between isolated success stories and widespread, sustainable adoption remains a central challenge—and a central opportunity—for agricultural development policy and practice in the years ahead.

Conclusion

The assessment of precision agriculture technologies in developing countries reveals both substantial promise and persistent complexity regarding their profitability. While a growing body of evidence demonstrates that precision agriculture can enhance yields, optimize input use, and improve environmental stewardship, these benefits are not evenly distributed across all farming contexts. Profitability is most consistently realized where farm size, infrastructure,

access to finance, and institutional support align to lower the barriers to adoption and facilitate effective use.

Comparisons with existing studies confirm that scale, local adaptation, and knowledge transfer remain central to successful integration of these technologies. Simple, context-sensitive innovations and collective models have proven especially valuable for smallholder farmers, helping to offset the high upfront costs and technical challenges that frequently hinder individual adoption. At the same time, robust extension services, public and private investment in digital infrastructure, and targeted policy interventions are vital in bridging knowledge and resource gaps, ensuring that precision agriculture technologies deliver sustainable financial returns.

However, it is equally clear that precision agriculture's value cannot be measured by short-term profitability alone. Broader benefits, including increased resilience to climate variability, reduced resource wastage, and improved environmental outcomes, contribute to the long-term viability and sustainability of farming systems. These indirect gains, though often less immediately quantifiable, reinforce the importance of adopting a holistic, system-oriented approach to agricultural innovation.

In conclusion, while precision agriculture offers transformative potential for developing countries, realizing consistent and widespread profitability requires more than access to technology. It demands an enabling ecosystem that combines investment, education, collective action, and supportive policies tailored to local realities. Only through such integrated and context-responsive strategies can the promise of precision agriculture be translated into tangible improvements in rural livelihoods and food security across the developing world.

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