Sarjana International Journal of Sustainable Food and Agriculture

Journal homepage:
https://sarjanaintelek.my/index.php/sijsfa/index
ISSN: 3093-7086

The Role of Synergistic Root-Soil-Fertilization Observation Devices in Enhancing Fertilizer Efficiency and Farmers' Income

Yutan Chen[1], Weijie Song[1], Weijie Song[1], Wenying Zhai[1], Yutan Chen[1], Can Hu[2,*], Xiaoqing Yuan[2,*]

[1] Deyang Agricultural College, Deyang 618500, Sichuan, China
[2] Technology R&D Center, Sichuan Teqi Tea Industry Ltd, Chengdu, Sichuan China

ARTICLE INFO

Article history:
Received 11 August 2026
Received in revised form 31 August 2026
Accepted 1 September 2026
Available online 15 September 2026

Keywords:

Precision agriculture; fertilizer efficiency; smart farming; sustainable agriculture; farmers' income; root-soil-fertilization observation device; IoT agriculture; agricultural sustainability

ABSTRACT

The increasing dependence on chemical fertilizers in modern agriculture has created significant environmental, economic, and sustainability challenges, including soil degradation, nutrient imbalance, environmental pollution, and rising production costs among farmers. In response to these challenges, precision agriculture technologies have emerged as important solutions for improving agricultural efficiency and sustainability. This study examines the role of synergistic root-soil-fertilization observation devices in enhancing fertilizer efficiency and improving farmers' income within the context of sustainable agriculture. The study integrates perspectives from the Diffusion of Innovation (DOI) Theory, Technology Acceptance Model (TAM), and Sustainable Agriculture Theory to explain the relationship between smart agricultural observation technologies, fertilizer optimization, and economic outcomes. The paper proposes a conceptual framework in which synergistic observation devices contribute to fertilizer efficiency through real-time monitoring, sensor integration, and precision nutrient management, which subsequently enhances farmers' income through improved productivity and cost reduction. The discussion highlights the importance of integrating smart farming technologies, Internet of Things (IoT) systems, and data-driven agricultural practices to support environmentally sustainable and economically viable farming systems. The study contributes to the literature on precision agriculture and sustainable farming by providing a theoretical foundation linking technological innovation, fertilizer efficiency, and farmers' welfare. The findings are expected to provide valuable implications for policymakers, agricultural practitioners, and researchers in promoting sustainable agricultural modernization and smart farming adoption.

* *Corresponding author.*
E-mail address: canhuphd@163.com, xiaoqingyuanphd@163.com

1. Introduction

Agriculture plays a critical role in ensuring global food security, economic development, and environmental sustainability. However, the agricultural sector is currently facing significant sustainability challenges due to climate change, population growth, resource scarcity, and increasing food demand. The global population is projected to exceed 9 billion by 2050, which is expected to substantially increase the demand for agricultural production while simultaneously placing greater pressure on natural resources and farming systems [25]. Consequently, modern agriculture is under increasing pressure to improve productivity while maintaining environmental sustainability and economic viability for farmers.

One of the major challenges confronting modern agriculture is excessive dependency on chemical fertilizers. Fertilizers are widely used to enhance crop productivity and maintain soil fertility; however, their inefficient and excessive application has created numerous environmental and economic problems. Conventional farming practices often apply fertilizers uniformly without considering soil variability, crop nutrient requirements, or environmental conditions, resulting in inefficient nutrient utilization and substantial fertilizer wastage [7]. Excessive fertilizer application not only increases production costs but also contributes to nutrient runoff, soil degradation, groundwater contamination, and greenhouse gas emissions, thereby threatening long-term agricultural sustainability.

Environmental degradation caused by chemical fertilizer overuse has become a growing global concern. Studies have shown that excessive nitrogen and phosphorus applications can lead to water pollution, eutrophication, soil acidification, and biodiversity loss [47]. In addition, the overreliance on chemical fertilizers has negatively affected soil health and reduced the long-term productivity of agricultural land. Such environmental consequences highlight the urgent need for sustainable fertilizer management strategies capable of balancing agricultural productivity with environmental conservation.

At the same time, rising fertilizer prices have imposed significant financial burdens on farmers worldwide. The increasing cost of agricultural inputs, particularly fertilizers, has reduced farmers' profitability and increased production risks, especially among smallholder farmers. High fertilizer expenditure directly affects operational costs and reduces net farm income, thereby threatening farmers' economic sustainability and livelihood stability. As a result, improving fertilizer efficiency has become an important strategy for reducing production costs while sustaining agricultural productivity [26].

The integration of sensors and agricultural analytics has become a core component of precision nutrient management. Sensors collect information concerning soil properties, crop conditions, weather, and nutrient status, while artificial intelligence (AI) and machine-learning techniques can be used to analyse these data and generate predictions or recommendations concerning crop nutrient requirements. In this context, AI should be understood primarily as a decision-support and optimisation mechanism rather than as a technology that independently reduces fertilizer application. Machine-learning-based nutrient-management systems can identify complex relationships among soil, crop, environmental, and management variables and use these relationships to support more precise fertilizer recommendations. When such recommendations are subsequently implemented through appropriate fertilizer-management or variable-rate application systems, they may improve nutrient-use efficiency and reduce unnecessary fertilizer inputs. Reviews of machine learning in nutrient management similarly indicate that these technologies have considerable potential for nutrient assessment and fertilizer decision support, although their effectiveness depends on data quality, model performance, sensing systems, and field implementation.

Smart farming technologies are particularly important in fertilizer management because they allow site-specific nutrient application and real-time monitoring of soil and crop conditions. Through the use of smart sensors and integrated monitoring systems, farmers can identify nutrient deficiencies, monitor soil moisture, and optimize fertilizer application according to crop needs. Previous studies have demonstrated that precision agriculture technologies can significantly reduce fertilizer usage while improving nutrient-use efficiency and crop productivity [7]. Furthermore, IoT-enabled systems have shown strong potential in enhancing resource efficiency, reducing operational costs, and supporting sustainable agricultural practices.

Among emerging smart farming innovations, root-soil-fertilization observation technologies have attracted increasing attention due to their ability to provide integrated and real-time agricultural monitoring. These technologies combine soil sensors, root monitoring systems, nutrient detection devices, and data analytics platforms to create synergistic monitoring systems capable of optimizing fertilizer management. Unlike traditional fertilizer management approaches, root-soil-fertilization observation systems provide comprehensive information regarding root development, soil nutrient conditions, and fertilizer distribution simultaneously, thereby enabling more accurate and efficient fertilization decisions.

The integration of root, soil, and fertilization data through advanced observation technologies represents a promising advancement in sustainable agriculture. Such systems can potentially improve fertilizer efficiency, reduce excessive fertilizer application, lower environmental impacts, and enhance farmers' income through improved productivity and reduced operational costs. Despite the growing development of precision agriculture technologies, studies examining the role of synergistic root–soil–fertilization observation devices in enhancing fertilizer efficiency and farmers' income remain limited. Therefore, this study seeks to address this gap by examining the potential role of these technologies in supporting sustainable agricultural productivity and economic sustainability among farmers.

1.1 Precision Agriculture and Smart Farming

Precision agriculture and smart farming have emerged as transformative approaches in modern agricultural systems, driven by the increasing need to improve productivity, reduce resource wastage, and ensure environmental sustainability. The evolution of precision agriculture began with the adoption of Global Positioning System (GPS) technologies, Geographic Information Systems (GIS), and remote sensing tools that enabled farmers to monitor spatial variability within agricultural fields. Over time, precision agriculture has evolved into a data-driven agricultural management system integrating digital technologies, automation, artificial intelligence (AI), Internet of Things (IoT), drones, and real-time analytics to optimize farming decisions and improve resource efficiency [21].

The concept of precision agriculture primarily focuses on site-specific crop management, where agricultural inputs such as fertilizers, pesticides, and irrigation are applied according to the actual needs of crops and soil conditions. This technological evolution has significantly shifted traditional farming practices toward intelligent and automated agricultural systems. According to recent developments in Agriculture 4.0, smart farming technologies integrate digital platforms, sensor networks, cloud computing, machine learning, and autonomous systems to enhance agricultural productivity while minimizing environmental impacts [6].

Digital farming systems represent one of the most important components of smart agriculture. These systems involve the use of digital tools and platforms for collecting, processing, analyzing, and sharing agricultural data throughout the farming process. Digital agriculture technologies include satellite imagery, mobile agricultural applications, drone monitoring systems, automated irrigation systems, cloud-based farm management software, and AI-driven decision-support systems [17]. These technologies enable farmers to make evidence-based decisions concerning crop management, fertilizer application, water utilization, and pest control. Furthermore, digital farming systems facilitate real-time monitoring and predictive analytics, allowing farmers to improve operational efficiency and reduce unnecessary agricultural input usage.

Smart monitoring technologies have further accelerated the modernization of agricultural systems. Recent advancements in IoT-based agriculture allow farmers to continuously monitor soil moisture, nutrient levels, weather conditions, crop health, and root-zone activities using interconnected sensors and wireless communication technologies. Real-time agricultural monitoring enhances farming precision by providing immediate information regarding field conditions and crop requirements. For instance, modern smart farming platforms integrate environmental sensors, satellite indices, AI-based analytics, and automated decision-support mechanisms to improve agricultural sustainability and productivity [6]. Similarly, advanced sensor systems have been developed to support real-time soil monitoring and wireless communication in smart agricultural applications, enabling efficient nutrient management and resource optimization [42].

The integration of sensors and agricultural analytics has become a core element in precision agriculture systems. Sensor technologies collect large volumes of agricultural data from soil, crops, weather conditions, and irrigation systems, while agricultural analytics transform these data into actionable insights for farmers. Through machine learning and AI-based analytical systems, smart farming technologies can predict crop stress, optimize fertilizer application, detect diseases, and support precision irrigation strategies. The integration of IoT sensors with agricultural analytics improves data accuracy, operational efficiency, and sustainable farm management practices [16]. Moreover, agricultural analytics facilitate predictive farming by identifying patterns and trends that support long-term agricultural planning and productivity enhancement.

Overall, the evolution of precision agriculture and smart farming demonstrates a major transformation from conventional agricultural practices toward intelligent, data-driven, and sustainable farming systems. The increasing integration of digital farming technologies, smart monitoring systems, and agricultural analytics provides substantial opportunities for improving fertilizer efficiency, enhancing crop productivity, reducing environmental degradation, and increasing farmers' income. Consequently, precision agriculture technologies, particularly synergistic root-soil-fertilization observation devices, are becoming increasingly important in achieving sustainable agricultural development and resource-efficient farming practices.

1.2 Root-Soil-Fertilization Observation Devices

Root-soil-fertilization observation devices refer to integrated precision agriculture technologies designed to monitor root-zone conditions, soil properties, and fertilizer dynamics simultaneously in real time to improve agricultural decision-making and resource efficiency. These systems combine sensors, Internet of Things (IoT) technologies, remote sensing tools, data analytics, and automated fertilization mechanisms to provide continuous information regarding soil nutrients, moisture conditions, root growth behavior, and crop nutrient requirements. The operational concept of these devices is based on the synchronization of below-ground biological and chemical interactions with fertilization management practices, allowing farmers to optimize fertilizer application according to actual crop needs rather than relying on traditional fixed schedules or generalized fertilization practices. Recent developments in precision agriculture emphasize that integrated monitoring technologies play an essential role in achieving sustainable agricultural production while reducing environmental degradation caused by excessive chemical fertilizer application [9,58].

Real-time soil and root monitoring systems represent a major advancement in modern smart farming practices. These systems utilize embedded soil sensors, wireless sensor networks, UAV remote sensing, spectroscopy, machine learning, and IoT-enabled monitoring tools to continuously collect and analyze field data associated with soil nutrient levels, soil moisture, root activity, pH balance, and crop growth conditions. Precision agriculture technologies enable farmers to receive timely and site-specific information, allowing immediate corrective actions and accurate nutrient management decisions. According to Chen, Zhang, and Wong [9], dynamic soil monitoring systems integrated with GIS and UAV technologies significantly improve nutrient prediction accuracy while reducing fertilizer input levels. Similarly, Monteiro *et al*., [36] explained that precision agriculture technologies support data-driven farming by improving spatial and temporal monitoring capabilities for crop and soil management. These technologies contribute to sustainable farming systems by enhancing nutrient-use efficiency and minimizing unnecessary fertilizer application.

Fertilizer optimization mechanisms are another important component of root-soil-fertilization observation devices. Fertilizer optimization refers to the process of applying fertilizers in precise quantities, locations, and timing according to crop nutrient requirements and soil conditions. Modern observation devices facilitate variable-rate fertilization, automated fertigation systems, nutrient prediction models, and intelligent recommendation systems that reduce fertilizer wastage while maximizing agricultural productivity. Precision fertilization systems supported by IoT and data analytics technologies are capable of improving fertilizer-use efficiency and lowering environmental pollution caused by nutrient leaching and excessive chemical accumulation in soils [29]. Furthermore, innovative fertilization strategies in precision agriculture integrate remote sensing, wireless sensor networks, and real-time analytics to ensure that fertilizers are applied only when and where they are required, thereby improving crop productivity and reducing operational costs [4]. These optimization mechanisms support sustainable agricultural intensification while maintaining soil health and environmental sustainability.

The synergistic integration of soil, root, and fertilization data forms the foundation of advanced smart agricultural systems. Traditional agricultural management often treats soil monitoring, crop observation, and fertilization practices as separate processes, resulting in inefficient resource allocation and inaccurate nutrient management. However, synergistic root-soil-fertilization observation systems integrate multiple datasets simultaneously to generate comprehensive and dynamic insights into crop nutrient demands and soil conditions. Through data fusion technologies, machine learning algorithms, and intelligent agricultural analytics, these systems improve the precision and responsiveness of fertilizer management practices. Recent studies have highlighted the importance of multi-source data integration in enhancing prediction accuracy and supporting precision nutrient management strategies [46,58]. Integrated observation technologies enable farmers to monitor interactions between soil conditions, root development, and fertilizer absorption processes in real time, thereby supporting sustainable agricultural productivity, reducing resource waste, and improving economic returns for farmers.

1.3 Fertilizer Efficiency and Sustainable Agriculture

Fertilizer efficiency has become one of the most critical components of sustainable agricultural development due to the increasing global demand for food production and the growing environmental concerns associated with excessive chemical fertilizer application. Fertilizer efficiency generally refers to the ability of crops to effectively absorb and utilize applied nutrients for optimal growth and productivity while minimizing nutrient losses to the environment. According to Nutrient Use Efficiency, fertilizer efficiency is closely associated with nutrient-use efficiency (NUE), which measures the proportion of applied nutrients that are successfully converted into agricultural output. Recent studies indicate that improving fertilizer efficiency is essential for balancing agricultural productivity, environmental protection, and economic sustainability in modern farming systems [40,52].

Nutrient-use efficiency has gained substantial attention in precision agriculture because conventional fertilizer practices often result in low nutrient absorption rates and significant nutrient losses through leaching, volatilization, and runoff. Liu *et al*., [31] reported that global nitrogen and phosphorus use efficiency remains below optimal levels in many agricultural systems, particularly in cereal crop production, leading to both economic inefficiency and environmental degradation. Similarly, Ye *et al*., [62] emphasized that enhancing fertilizer-use efficiency contributes significantly to sustainable agricultural development by improving land productivity while reducing excessive fertilizer dependency. Improved nutrient-use efficiency can also reduce production costs for farmers because less fertilizer input is required to achieve comparable or higher crop yields.

Various fertilizer reduction strategies have been introduced to improve agricultural sustainability and reduce environmental pressure. These strategies include precision fertilization, controlled-release fertilizers, integrated nutrient management, soil nutrient monitoring systems, and sensor-based smart farming technologies. Enhanced efficiency fertilizers are specifically designed to minimize nutrient losses and optimize nutrient delivery to crops, thereby increasing fertilizer-use efficiency and improving soil health. In addition, precision agriculture technologies that integrate soil, root, and nutrient monitoring systems allow farmers to apply fertilizers according to real-time crop requirements rather than relying on conventional blanket fertilization methods. Such approaches significantly reduce fertilizer wastage and improve resource utilization efficiency [24].

Environmental sustainability is strongly linked to fertilizer efficiency because excessive fertilizer application has been associated with soil degradation, water contamination, greenhouse gas emissions, and biodiversity loss. Penuelas *et al*., [40] argued that although fertilizers have substantially increased global food production over recent decades, inefficient fertilizer utilization has generated severe ecological consequences and nutrient imbalances in agricultural ecosystems. Furthermore, recent agricultural sustainability studies emphasize that improving fertilizer-use efficiency is necessary to minimize non-point source pollution and preserve long-term soil fertility [63]. Sustainable fertilizer management therefore aims to achieve a balance between maximizing crop productivity and minimizing environmental damage through more efficient nutrient management systems.

Resource optimization in farming systems has also become increasingly important in modern sustainable agriculture frameworks. Efficient resource utilization involves optimizing fertilizer input, water usage, energy consumption, and land productivity simultaneously to maximize agricultural output with minimal environmental impact. Sharafi *et al*., [52] found that improvements in fertilizer-use efficiency contributed to higher crop production while reducing fertilizer intensity per unit of yield, demonstrating the importance of resource-efficient farming systems. Similarly, sustainable nutrient management technologies, including real-time monitoring systems and intelligent agricultural analytics, enable farmers to make data-driven fertilization decisions that enhance productivity while conserving agricultural resources. Consequently, fertilizer efficiency serves not only as an agronomic indicator but also as a strategic mechanism for promoting sustainable agricultural transformation and long-term economic resilience among farming communities.

1.4 Farmers' Income and Agricultural Productivity

Agricultural productivity plays a critical role in improving farmers' income and ensuring the sustainability of rural economies. Productivity in agriculture refers to the efficient utilization of production inputs, such as land, labor, water, and fertilizers, to generate higher agricultural outputs and economic returns. Recent studies have emphasized that improving productivity not only enhances food security but also contributes significantly to farmers' profitability and long-term economic welfare. Technological advancement, precision agriculture, and sustainable fertilizer management have become increasingly important mechanisms for increasing agricultural productivity while minimizing production costs and environmental degradation [13,44].

Agricultural profitability is closely associated with farmers' ability to maximize output while minimizing operational costs. Rising fertilizer prices, labor shortages, and climate-related uncertainties have placed significant financial pressure on farming communities worldwide. Studies have shown that inefficient fertilizer application often increases production costs without proportionally improving crop yields, thereby reducing farm profitability [2]. In response, precision farming technologies and soil-testing systems have emerged as important solutions to optimize input utilization and improve profit margins. Research by Ren *et al.*, [44] demonstrated that precision nutrient management significantly reduced fertilizer costs while simultaneously increasing net farm income and fertilizer-use efficiency.

Cost reduction mechanisms are essential for improving farmers' economic resilience and sustainability. The adoption of smart agricultural technologies, including precision fertilization systems and observation devices, enables farmers to reduce unnecessary fertilizer application, minimize resource wastage, and improve operational efficiency. Li *et al.*, [28] found that soil-testing-based fertilizer application and agricultural outsourcing services significantly enhanced farmers' income through more efficient nutrient management practices. Similarly, studies have indicated that optimized fertilizer usage contributes to lower production expenditures and enhances overall farm profitability, particularly among smallholder farmers who are highly sensitive to fluctuations in input prices [23].

Yield improvement remains one of the most important determinants of farmers' income. Higher agricultural productivity allows farmers to generate larger harvest volumes, improve product quality, and increase market competitiveness. Sustainable fertilizer management practices, combined with precision agriculture technologies, have been shown to enhance nutrient absorption efficiency and crop performance. Daemo *et al.*, [13] reported that optimized fertilizer application significantly increased maize yield and profitability among farming households. Furthermore, Li *et al.*, [28] observed that fertilizer optimization supported by soil-testing formulas substantially improved wheat yields and farmers' net income. These findings suggest that technology-assisted fertilizer management can improve both productivity and economic outcomes in agricultural systems.

Long-term economic sustainability is increasingly recognized as a fundamental objective of modern agriculture. Sustainable farming practices not only improve short-term profitability but also preserve soil fertility, environmental quality, and resource availability for future agricultural production. Agricultural diversification, precision agriculture, and sustainable nutrient management have been identified as key drivers of long-term economic resilience among farmers. Raveloaritiana and Wanger [43] highlighted that sustainable agricultural diversification practices substantially improve long-term profitability, biodiversity, and ecosystem services over time. In addition, sustainable productivity growth contributes to stable farm income, improved rural livelihoods, and reduced vulnerability to market and climate-related shocks [8]. Therefore, integrating synergistic root–soil–fertilization observation technologies into farming systems may provide substantial opportunities for enhancing fertilizer efficiency, increasing agricultural productivity, and supporting the long-term economic sustainability of farmers.

1.5 Theoretical Foundation

This study draws upon the Diffusion of Innovation (DOI) Theory and the Technology Acceptance Model (TAM) as complementary theoretical lenses for explaining the adoption and effective utilisation of synergistic root-soil-fertilization observation devices. The use of both perspectives is appropriate because farmers' adoption of smart agricultural technologies involves two related but conceptually distinct considerations: the perceived characteristics of the innovation itself and the farmer's evaluation of whether the technology is useful and sufficiently easy to use. DOI primarily explains the innovation-related characteristics that influence adoption, whereas TAM focuses on users' cognitive evaluations that shape technology acceptance and utilisation.

The Diffusion of Innovation Theory developed by Rogers explains how the characteristics of an innovation influence its adoption and diffusion within a social system. Five attributes are particularly relevant: relative advantage, compatibility, complexity, trialability, and observability. In the context of synergistic root-soil-fertilization observation devices, relative advantage concerns whether farmers perceive the technology as providing benefits over conventional fertilizer-management practices, such as more accurate nutrient information, lower fertilizer wastage, or improved productivity. Compatibility reflects the extent to which the system can be integrated with existing farming practices and infrastructure, while complexity concerns the difficulty associated with operating sensors, interpreting monitoring data, and applying technology-generated recommendations. Trialability allows farmers to experiment with the technology before full adoption, whereas observability concerns whether improvements in fertilizer management, crop performance, or economic outcomes can be readily observed. These innovation characteristics are particularly important in agriculture, where technology adoption can be constrained by implementation costs, technical knowledge, infrastructure, and uncertainty regarding economic returns.

TAM complements DOI by explaining how farmers evaluate the technology from a user-oriented perspective. According to Davis [14], perceived usefulness refers to the extent to which an individual believes that using a technology will improve performance, while perceived ease of use concerns the extent to which the technology can be used with relatively little effort. For synergistic root-soil-fertilization observation devices, perceived usefulness may arise when farmers believe that real-time monitoring and integrated root, soil, and nutrient information can improve fertilizer decisions, reduce unnecessary input expenditure, or enhance crop performance. Perceived ease of use is equally relevant because systems requiring complicated sensor operation, data interpretation, or technical maintenance may discourage adoption, particularly where farmers have limited digital skills or access to technical support.

The integration of DOI and TAM is therefore based on their complementary explanatory roles rather than on treating the two theories as interchangeable. DOI explains how the perceived attributes of the innovation influence its attractiveness and adoption, whereas TAM explains how users evaluate the technology in terms of usefulness and ease of use. Conceptually, these processes may also interact. For example, a strong relative advantage may reinforce perceived usefulness, while greater technological complexity may reduce perceived ease of use. Similarly, compatibility with existing farming practices may strengthen farmers' perceptions that the technology is both useful and manageable. Thus, DOI provides an innovation-level explanation, while TAM provides a user-level explanation of technology acceptance.

Within the proposed framework, DOI and TAM are not treated as additional empirical variables. Instead, they provide the theoretical rationale for explaining why synergistic root-soil-fertilization observation devices may be adopted and effectively utilised. The proposed framework then extends beyond technology adoption by explaining what may occur after effective utilisation. Specifically, the technological capabilities of integrated observation devices including real-time monitoring, sensor integration, data accuracy, and fertilizer recommendation support are proposed to improve fertilizer efficiency. Improved fertilizer efficiency may subsequently contribute to farmers' income through reduced fertilizer expenditure, improved productivity, and more efficient resource utilisation.

Accordingly, the theoretical mechanism proposed in this study can be expressed as follows:

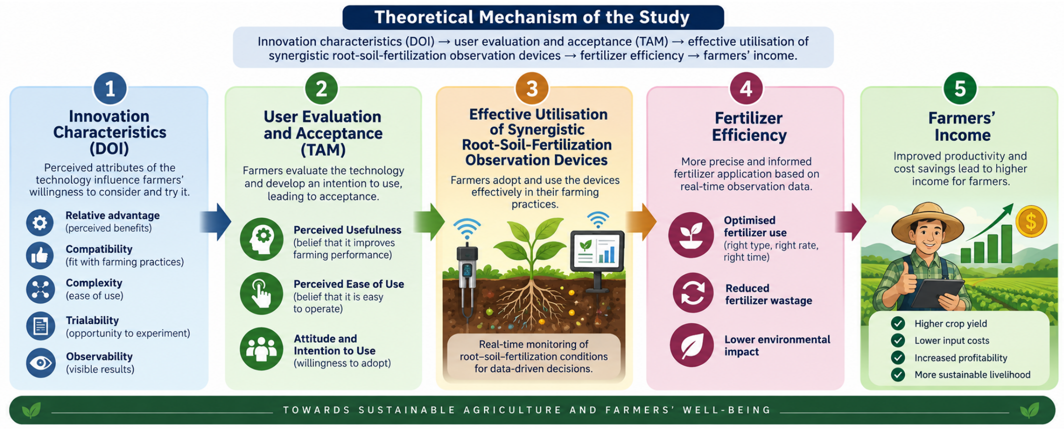

Fig. 1. Theoretical mechanism

Sustainable agriculture provides the broader outcome-oriented perspective for this mechanism. The effective use of precision observation technologies may support more efficient nutrient management, reduced fertilizer wastage, and improved resource utilisation, while fertilizer efficiency may contribute to both environmental sustainability and farmers' economic viability. However, because the present study is conceptual, these relationships represent theoretically derived propositions rather than empirically established causal relationships. Future empirical research is therefore required to test the proposed mechanism and determine the conditions under which technology adoption and utilisation translate into fertilizer-efficiency and economic outcomes.

1.6 Research Gap, Significance, and Objectives

The increasing global demand for agricultural productivity has intensified the use of chemical fertilizers in modern farming systems. Although fertilizers play an important role in improving crop yields, excessive and inefficient fertilizer application has contributed to severe environmental degradation, including soil acidification, water contamination, greenhouse gas emissions, and declining soil fertility [30,64]. In response to these challenges, precision agriculture technologies have emerged as a promising solution for improving nutrient management and supporting sustainable agricultural practices. Among these technologies, root-soil-fertilization observation systems have gained growing attention due to their capability to monitor soil conditions, root development, and nutrient dynamics simultaneously in real time [59].

Despite the growing development of smart farming technologies, existing studies remain fragmented and largely focus on isolated agricultural monitoring systems rather than integrated root-soil-fertilization observation mechanisms. Most current agricultural monitoring technologies emphasize either soil nutrient monitoring, irrigation systems, or crop growth analysis independently, without establishing synergistic integration among root systems, soil conditions, and fertilization management [10]. Consequently, there remains limited understanding regarding how integrated observation devices can optimize fertilizer utilization in a holistic agricultural ecosystem.

Furthermore, previous studies have predominantly concentrated on crop productivity and yield enhancement as the primary indicators of agricultural technology performance [28]. While crop productivity is an important agricultural outcome, fertilizer efficiency remains comparatively underexplored despite its direct relationship with sustainable farming and environmental preservation. Fertilizer efficiency is increasingly recognized as a critical factor in reducing agricultural waste, minimizing production costs, and promoting sustainable resource utilization [18]. However, limited studies have investigated how synergistic observation technologies specifically contribute to fertilizer optimization and nutrient-use efficiency.

Another important research gap concerns the limited examination of the economic implications of smart agricultural observation technologies for farmers. Existing precision agriculture studies frequently emphasize technological performance and crop output while paying insufficient attention to farmers' income and economic sustainability [55]. Farmers' income is strongly influenced by production efficiency, input costs, and yield quality. Therefore, understanding how fertilizer efficiency contributes to economic benefits is essential for ensuring the practical sustainability and adoption of agricultural technologies among farming communities.

From a theoretical perspective, technology-adoption theories such as DOI and TAM have been widely applied in agricultural technology research, and previous studies have demonstrated the value of combining innovation-related and user-acceptance perspectives in explaining precision-technology adoption. Nevertheless, considerably less attention has been directed toward explaining how technology adoption and effective utilisation may subsequently translate into operational resource efficiency and farmers' economic outcomes. In particular, the post-adoption mechanism connecting the effective utilisation of integrated root-soil-fertilization observation technologies with fertilizer efficiency and, subsequently, farmers' income remains insufficiently conceptualised. The present study therefore does not claim novelty merely from combining DOI and TAM; rather, it extends their complementary adoption-oriented logic by linking technology acceptance and effective utilisation to fertilizer efficiency as an operational mechanism and farmers' income as a subsequent economic outcome.

Moreover, insufficient conceptual frameworks currently exist that integrate synergistic root-soil-fertilization observation devices, fertilizer efficiency, and farmers' income within a single model. Most previous studies examine these variables independently, resulting in fragmented findings and limited understanding of the mediating mechanisms connecting agricultural technology adoption to economic outcomes [57]. Therefore, a comprehensive framework is needed to explain how smart observation technologies can improve fertilizer efficiency, which subsequently enhances farmers' income and agricultural sustainability.

Based on these gaps, the present study addresses the research problem concerning the limited understanding of how synergistic root-soil-fertilization observation devices contribute to fertilizer efficiency and farmers' economic outcomes. This study is important because it integrates technological, environmental, and economic perspectives into a unified conceptual framework. The study also provides a theoretical and practical foundation for advancing precision agriculture, reducing fertilizer dependency, and promoting sustainable agricultural development.

This study aims to examine the role of synergistic root-soil-fertilization observation devices in enhancing fertilizer efficiency and to investigate the relationship between fertilizer efficiency and farmers' income. In addition, the study seeks to examine the mediating role of fertilizer efficiency in the relationship between synergistic root-soil-fertilization observation devices and farmers' income, thereby providing a comprehensive understanding of how smart agricultural observation technologies contribute to sustainable agricultural productivity and economic outcomes for farmers.

This study provides several important contributions from theoretical, practical, and social perspectives. Theoretically, the study extends the literature on precision agriculture by integrating smart agricultural observation technologies with fertilizer efficiency and farmers' economic outcomes. The study also contributes to the integration of the Technology Acceptance Model (TAM), Diffusion of Innovation (DOI) theory, and sustainable agriculture perspectives within agricultural technology research.

Practically, the study offers valuable insights for policymakers, agricultural technology developers, and farming communities regarding the implementation of smart agricultural observation systems. The proposed framework may assist agricultural stakeholders in developing effective fertilizer management strategies that improve resource efficiency while reducing production costs and environmental impacts.

Socially and environmentally, the study contributes to sustainable agricultural development by promoting environmentally responsible fertilizer utilization and supporting long-term food security. Improved fertilizer efficiency may reduce excessive chemical fertilizer application, minimize environmental pollution, and enhance the economic sustainability of farmers, particularly in developing agricultural regions.

2. Methodology

2.1 Research Design

This study adopts a quantitative research approach to examine the relationships between synergistic root-soil-fertilization observation devices, fertilizer efficiency, and farmers' income. Quantitative research is widely used in agricultural and technology-related studies because it enables researchers to systematically measure variables, test hypotheses, and examine causal relationships through statistical analysis. According to Ghanad [20], quantitative research emphasizes objective measurement, numerical data analysis, and statistical modelling to explain relationships among variables. Similarly, Nwabuko *et al*., [37] explained that quantitative research designs provide a structured mechanism for data collection and analysis, thereby enhancing the reliability and validity of research findings. In the context of this study, the quantitative approach is considered appropriate because it allows for the empirical assessment of how agricultural monitoring technologies influence fertilizer efficiency and economic outcomes among farmers.

The study further employs a cross-sectional research design, where data are collected from respondents at a single point in time. Cross-sectional studies are commonly used in social science, agricultural, and technology adoption research due to their efficiency in examining relationships among variables within a defined population. Wang and Cheng [60] described cross-sectional studies as observational designs that analyze data from a population at one specific time period to identify associations between variables. Likewise, Maier *et al*., [33] noted that cross-sectional designs are suitable for investigating perceptions, behaviors, and technological adoption patterns because they enable researchers to obtain a broad overview of a phenomenon within a relatively short timeframe. The cross-sectional design is particularly suitable for this study because it facilitates the examination of farmers' current adoption and perception of synergistic root–soil–fertilization observation devices and their influence on fertilizer management practices and income generation.

In addition, this study develops a conceptual model to explain the relationships among the proposed variables. The conceptual model serves as a theoretical representation that integrates agricultural technology adoption, fertilizer efficiency, and economic sustainability within a single framework. The model proposes that synergistic root–soil–fertilization observation devices positively influence fertilizer efficiency, which subsequently enhances farmers' income. The development of the conceptual model is supported by existing theoretical perspectives, including the Diffusion of Innovation (DOI) Theory and the Technology Acceptance Model (TAM), which explain how technological innovations are adopted and utilized to improve performance outcomes. Conceptual model development is important in quantitative research because it provides a structured foundation for hypothesis formulation and empirical testing. As emphasized by Ghanad [20], quantitative studies frequently utilize conceptual models to identify variable relationships and establish theoretical direction prior to statistical analysis. Therefore, the proposed conceptual model provides a comprehensive framework for understanding how smart agricultural observation technologies may contribute to sustainable farming practices and economic improvement among farmers.

2.2 Model Development

The conceptual model of this study is developed to explain how synergistic root–soil–fertilization observation devices contribute to fertilizer efficiency and subsequently improve farmers' income. The model integrates perspectives from precision agriculture, smart farming technologies, and sustainable agriculture theories to explain the mechanism through which technological innovation enhances both agricultural productivity and economic sustainability. The conceptual framework proposes that advanced agricultural observation technologies enable farmers to optimize fertilizer application through real-time monitoring of root conditions, soil nutrient status, and fertilization requirements, thereby improving fertilizer-use efficiency and increasing farm profitability.

The proposed mechanism distinguishes between technology adoption and the operational consequences of technology utilisation. DOI and TAM primarily provide theoretical explanations for the former stage. DOI explains how characteristics of synergistic observation technologies may influence farmers' willingness to adopt them, while TAM explains how perceived usefulness and perceived ease of use may shape acceptance and utilisation. However, adoption alone does not necessarily generate fertilizer-efficiency or economic benefits. Such outcomes depend on whether the technology is effectively incorporated into fertilizer-management practices. The conceptual framework therefore extends the adoption process toward an operational pathway in which effective utilisation of observation technologies improves fertilizer efficiency, which subsequently contributes to farmers' income through cost savings and productivity enhancement.

The relationship between observation devices and fertilizer efficiency is grounded in the principles of precision agriculture and smart farming systems. Modern agricultural monitoring technologies, including Internet of Things (IoT)-based sensors, artificial intelligence systems, and real-time soil monitoring devices, have significantly transformed fertilizer management practices by enabling site-specific nutrient application and data-driven agricultural decision-making. Recent studies indicate that precision agriculture technologies enhance nutrient-use efficiency by reducing fertilizer wastage, improving soil monitoring accuracy, and supporting optimized fertilizer application timing [7,26]. Advanced monitoring systems provide continuous information regarding soil moisture, nutrient levels, root health, and environmental conditions, enabling farmers to apply fertilizers according to actual crop requirements rather than relying on conventional blanket fertilization methods [34].

In addition, the synergistic integration of root, soil, and fertilization monitoring systems allows farmers to better understand nutrient absorption processes and soil variability across agricultural fields. According to Karunathilake *et al.*, [25], precision agriculture technologies improve agricultural sustainability by maximizing crop output while minimizing unnecessary agricultural inputs and environmental damage. Similarly, Sanyaolu *et al*., [47] argued that precision agricultural systems contribute to significant reductions in fertilizer use without negatively affecting crop productivity. These technologies support sustainable nutrient management by facilitating targeted fertilizer application, improving nutrient absorption efficiency, and minimizing excessive fertilizer dependency. Therefore, synergistic root–soil–fertilization observation devices are expected to positively influence fertilizer efficiency through improved monitoring accuracy, precision nutrient management, and optimized resource utilization.

The relationship between fertilizer efficiency and farmers' income is associated with the economic benefits generated through optimized agricultural resource management. Fertilizer efficiency refers to the ability of farmers to maximize crop productivity while minimizing fertilizer input costs and environmental losses. Efficient fertilizer management reduces unnecessary expenditure on chemical fertilizers, improves crop yield quality, and enhances overall farm profitability. Precision agriculture techniques have been shown to significantly improve agricultural productivity and cost efficiency by enabling more accurate fertilizer application and reducing operational waste [7]. As fertilizer costs continue to increase globally, improving fertilizer-use efficiency has become increasingly important for enhancing farmers' economic sustainability and long-term profitability.

Furthermore, smart farming technologies contribute to farmers' income through improved productivity, reduced production costs, and enhanced decision-making capabilities. Kumar *et al*., [26] emphasized that IoT-enabled agricultural systems improve agricultural sustainability by optimizing resource allocation and minimizing input wastage. Similarly, studies on smart farming technologies suggest that digital agricultural systems improve crop quality, increase productivity, and support better farm management decisions, ultimately contributing to higher farmer income and rural economic development [11]. Precision fertilizer management also reduces environmental degradation and soil deterioration, which supports long-term agricultural productivity and economic resilience. Consequently, higher fertilizer efficiency is expected to positively influence farmers' income through cost savings, productivity enhancement, and sustainable agricultural performance.

The mediation mechanism proposed in this study suggests that fertilizer efficiency acts as an intermediary variable linking synergistic root–soil–fertilization observation devices and farmers' income. In this mechanism, the observation devices themselves may not directly increase farmers' income unless they first improve fertilizer management efficiency. The technological capability of the observation systems enables farmers to optimize fertilizer application, reduce input waste, and improve nutrient-use efficiency, which subsequently contributes to higher agricultural profitability and improved economic outcomes. This mediation perspective is consistent with sustainable agriculture theories, which emphasize that technological innovation contributes to economic sustainability through operational and resource efficiency improvements.

Recent literature on precision agriculture supports the indirect economic benefits of smart farming technologies through enhanced resource optimization and operational efficiency. Emerging smart farming systems integrate IoT sensors, artificial intelligence, cloud computing, and data analytics to improve decision-making accuracy and agricultural productivity [39]. These technologies enable farmers to identify soil nutrient deficiencies, monitor crop conditions in real time, and implement variable-rate fertilization strategies that improve efficiency and profitability. As a result, fertilizer efficiency serves as the key mechanism through which agricultural observation technologies translate technological innovation into economic value for farmers. Therefore, this study proposes that fertilizer efficiency mediates the relationship between synergistic root–soil–fertilization observation devices and farmers' income.

2.3 Hypothesis Development

The rapid advancement of precision agriculture technologies has transformed traditional farming practices into data-driven agricultural systems capable of improving resource utilization and environmental sustainability. Synergistic root–soil–fertilization observation devices integrate sensor technologies, real-time monitoring systems, and agricultural analytics to provide accurate information regarding soil nutrient conditions, root development, and fertilizer requirements. These technologies enable farmers to optimize fertilizer application according to actual crop and soil needs, thereby reducing excessive fertilizer usage and enhancing nutrient-use efficiency. Recent studies have emphasized that precision agriculture technologies significantly contribute to fertilizer optimization by facilitating targeted nutrient management and minimizing nutrient losses caused by over-application [7,26].

Furthermore, smart farming systems supported by IoT, sensor integration, and real-time agricultural monitoring have demonstrated substantial improvements in resource efficiency and precision fertilization management. Singh and Singh [53] explained that IoT-enabled precision agriculture systems improve communication between agricultural monitoring devices and farming operations, allowing more accurate fertilizer recommendations and efficient nutrient delivery. Similarly, Padhiary *et al*., [39] argued that nutrient sensors and soil-monitoring technologies facilitate precise fertilizer delivery by providing real-time information on soil fertility conditions, which directly improves nutrient management efficiency. In addition, precision agriculture technologies reduce fertilizer wastage and environmental degradation through data-driven decision-making and site-specific nutrient management strategies [38].

The Diffusion of Innovation (DOI) Theory further supports the argument that innovative agricultural technologies improve farming performance when farmers perceive the technologies as useful and beneficial. The integration of synergistic root–soil–fertilization observation devices may therefore increase fertilizer efficiency by enabling accurate nutrient application, reducing fertilizer losses, and supporting sustainable farming practices. Based on the above discussion, the following hypothesis is proposed:

H1: Synergistic root–soil–fertilization observation devices significantly enhance fertilizer efficiency.

Fertilizer efficiency plays a critical role in improving agricultural productivity and farmers' economic performance. Efficient fertilizer utilization enables farmers to reduce unnecessary fertilizer expenses while simultaneously improving crop growth, productivity, and product quality. Precision nutrient management strategies reduce production costs and enhance profitability through optimized input allocation and improved crop yields. According to Cai *et al*., [7], precision agriculture techniques significantly improve nutrient-use efficiency by preventing fertilizer over-application and ensuring that nutrients are delivered according to crop requirements. These improvements subsequently contribute to higher agricultural productivity and reduced environmental costs.

Moreover, fertilizer efficiency contributes directly to economic sustainability by reducing operational costs associated with excessive fertilizer dependency. Precision agriculture systems supported by smart technologies improve resource optimization and profitability by enhancing crop monitoring and data-driven farming decisions [26]. Research conducted by Li *et al*., [28] further demonstrated that fertilizer management strategies supported by soil-testing technologies significantly increase farmers' net income through improved crop yields and efficient nutrient management. The study revealed that fertilizer application integrated with soil-testing formulas substantially increased wheat farmers' income due to higher production efficiency and better nutrient utilization.

In addition, smart farming technologies contribute to sustainable agricultural profitability by improving crop productivity, reducing fertilizer waste, and increasing farm operational efficiency [54]. Precision agriculture systems allow farmers to allocate agricultural inputs more effectively, thereby increasing agricultural returns while minimizing unnecessary expenditures. From the perspective of Sustainable Agriculture Theory, efficient resource utilization enhances both environmental sustainability and long-term economic viability for farmers. Therefore, fertilizer efficiency may positively influence farmers' income through cost reduction and productivity enhancement mechanisms. Based on these arguments, the following hypothesis is proposed:

H2: Fertilizer efficiency significantly improves farmers' income.

The relationship between synergistic root–soil–fertilization observation devices and farmers' income may not occur directly, but rather through improvements in fertilizer efficiency. Smart agricultural observation technologies primarily function by collecting and analyzing real-time agricultural data that support precision nutrient management and optimized fertilizer application. Consequently, the economic benefits generated by these technologies are likely achieved through enhanced fertilizer efficiency, which subsequently improves agricultural productivity and profitability.

Previous studies have shown that precision agriculture technologies enhance farm performance by improving resource utilization efficiency and reducing production costs [26,38]. Real-time monitoring technologies enable farmers to identify nutrient deficiencies accurately and apply fertilizers only where necessary, thereby improving nutrient-use efficiency and reducing fertilizer wastage [39]. Through these mechanisms, fertilizer efficiency becomes an important pathway linking agricultural technology adoption and economic outcomes.

Furthermore, Li *et al*., [28] highlighted that fertilizer management supported by soil-testing systems improves farmers' income primarily through enhanced crop yields and optimized fertilizer utilization. This finding suggests that fertilizer efficiency serves as an underlying mechanism through which smart agricultural technologies generate economic benefits for farmers. From the perspectives of DOI Theory and Sustainable Agriculture Theory, technological innovations improve farm performance when they successfully optimize resource management practices and increase operational efficiency.

Accordingly, synergistic root–soil–fertilization observation devices may indirectly improve farmers' income by increasing fertilizer efficiency, reducing production costs, and enhancing agricultural productivity. Therefore, fertilizer efficiency is expected to function as a mediating variable in the relationship between observation devices and farmers' income. Based on this discussion, the following hypothesis is proposed:

H3: Fertilizer efficiency mediates the relationship between synergistic root–soil–fertilization observation devices and farmers' income.

2.6 Conceptual Framework

The conceptual framework of this study illustrates the proposed relationships between synergistic root-soil-fertilization observation devices, fertilizer efficiency, and farmers' income within the context of sustainable and precision agriculture. The framework positions synergistic root-soil-fertilization observation devices as the independent variable, reflecting the integration of real-time monitoring capability, sensor integration, data accuracy, and fertilizer recommendation support in modern agricultural systems. These technological capabilities are expected to improve fertilizer efficiency by enabling more precise nutrient management, reducing fertilizer wastage, and optimizing resource utilization. Fertilizer efficiency is conceptualized as the mediating variable because it represents the primary mechanism through which smart agricultural technologies influence farming performance and economic outcomes. Improved fertilizer efficiency is subsequently expected to enhance farmers' income through increased profitability, higher crop yields, reduced operational costs, and greater economic sustainability.

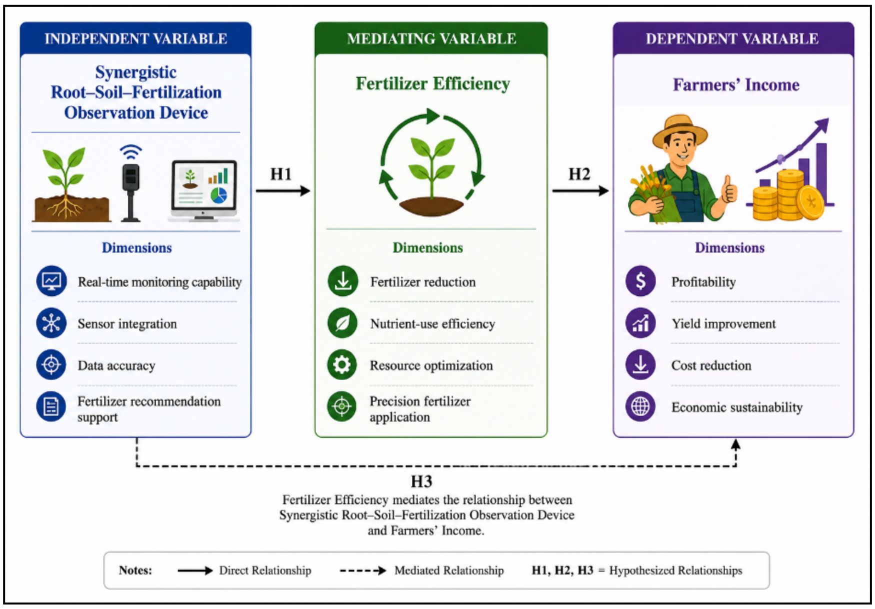

Fig. 2. Conceptual framework

The framework further proposes that fertilizer efficiency mediates the relationship between observation devices and farmers' income, indicating that the economic benefits of smart agricultural technologies are achieved indirectly through optimized fertilizer management practices. The proposed conceptual framework is grounded in the Diffusion of Innovation Theory (DOI), Technology Acceptance Model (TAM), and Sustainable Agriculture Theory, which collectively explain technology adoption behavior, resource optimization, and sustainable agricultural development.

3. Discussion

3.1 Observation Devices and Fertilizer Efficiency

The integration of synergistic root-soil-fertilization observation devices has significantly transformed precision fertilizer management in modern agriculture. Precision fertilizer management refers to the application of fertilizers based on the actual nutrient requirements of crops through real-time monitoring and site-specific agricultural practices. Unlike conventional fertilization methods that apply fertilizers uniformly across agricultural fields, precision agriculture technologies enable farmers to optimize nutrient application according to soil conditions, crop growth stages, and root nutrient absorption patterns. Recent advancements in Internet of Things (IoT), sensor technologies, artificial intelligence (AI), and machine learning have accelerated the implementation of precision fertilizer management systems, allowing farmers to improve nutrient-use efficiency while reducing environmental impacts [4,7].

Synergistic root-soil-fertilization observation devices contribute to fertilizer efficiency by continuously monitoring soil nutrient conditions, moisture levels, root growth dynamics, and crop nutrient demands in real time. These technologies enable site-specific nutrient management, whereby fertilizers are applied only when and where they are required. According to Cai *et al*., [7], precision agriculture technologies fundamentally improve fertilizer management by integrating remote sensing, soil sampling, and GPS-guided systems to optimize nutrient application and minimize excessive fertilizer use. Similarly, Karunathilake *et al*., [25] highlighted that precision agriculture utilizes advanced technologies such as sensors, drones, and big data analytics to maximize agricultural productivity while reducing unnecessary agricultural inputs and environmental degradation.

One of the most important contributions of observation devices is the reduction of fertilizer wastage. Traditional fertilization approaches often result in over-application due to farmers' limited access to accurate soil and crop nutrient information. Excessive fertilizer application not only increases production costs but also contributes to soil degradation, water pollution, greenhouse gas emissions, and nutrient runoff. Precision observation devices address these challenges by providing accurate, real-time data that guide fertilizer application decisions. Kumar *et al*., [4] explained that IoT-enabled smart farming technologies improve resource efficiency and reduce resource wastage through continuous monitoring and data-driven farm management systems. Likewise, Sanyaolu *et al.*, [47] reported that precision agriculture can reduce mineral fertilizer usage by approximately 15% without negatively affecting crop yields, thereby enhancing both environmental and economic sustainability.

In addition, observation devices facilitate data-driven agricultural decision-making, which has become a critical component of smart farming systems. Data-driven agriculture relies on the collection, integration, and analysis of agricultural data to support informed management decisions. Smart observation systems combine sensor technologies, cloud computing, AI, and machine learning algorithms to analyse soil fertility, weather conditions, crop growth, and nutrient absorption patterns. This allows farmers to make timely and accurate decisions regarding fertilizer application schedules and quantities. Manono *et al*., [34] emphasized that smart sensors provide continuous real-time insights into soil moisture, temperature, humidity, and nutrient levels, enabling predictive analysis and dynamic farm management decisions. Similarly, Padhiary *et al*., [39] argued that the integration of automation, AI, cloud computing, and IoT technologies enhances agricultural productivity through improved decision-making capabilities and efficient resource management.

Furthermore, synergistic observation devices support sustainable nutrient management by promoting balanced fertilizer application and minimizing environmental risks associated with chemical fertilizer overuse. Sustainable nutrient management aims to improve agricultural productivity while preserving soil health, water quality, and ecosystem sustainability. Precision observation systems contribute to sustainability by ensuring that nutrients are supplied according to crop requirements, thereby reducing nutrient losses and environmental contamination. Research by Cai *et al*., [7] demonstrated that precision agriculture technologies improve nutrient-use efficiency and sustainability by enabling targeted fertilizer application and continuous soil monitoring. Additionally, Jararweh *et al*., [22] noted that smart and sustainable agriculture technologies provide long-term solutions for food security, resource optimization, and environmental protection through intelligent agricultural management systems.

Artificial intelligence may further strengthen fertilizer management when it is integrated with sensor-based monitoring and precision application systems. However, the contribution of AI should be distinguished from the functions of the sensing and application technologies themselves. Sensors generate information concerning soil, crop, and nutrient conditions, while AI and machine-learning models can analyse these data to identify patterns, predict nutrient requirements, or generate fertilizer recommendations. The resulting fertilizer savings occur when these recommendations are translated into appropriate nutrient-management decisions or variable-rate applications rather than from the AI algorithm alone.

Empirical evidence increasingly supports this mechanism. For example, an AI-based nutrient-management system integrating real-time sensor information with artificial neural networks was reported to reduce nutrient use by up to 40% in hydroponic lettuce without compromising plant growth and yield. Similarly, a deep-learning-assisted variable-rate fertilizer application system developed for wheat used image-based nitrogen-stress detection to regulate fertilizer application and achieved an average nitrogen fertilizer saving of approximately 37.5% compared with the traditional application technique while maintaining comparable yield performance. These findings provide evidence that AI-supported nutrient management can improve fertilizer-use efficiency when predictive algorithms are effectively integrated with reliable sensing and precision application mechanisms.

Nevertheless, these results should not be interpreted as evidence that AI technologies inherently or universally reduce fertilizer use. The magnitude of fertilizer savings depends on factors including crop type, baseline fertilizer practice, soil variability, sensor accuracy, data quality, model reliability, environmental conditions, application equipment, and the extent to which AI-generated recommendations are implemented correctly. AI should therefore be conceptualised as an enabling component of an integrated precision nutrient-management system rather than as an independent determinant of fertilizer reduction.

Overall, synergistic root-soil-fertilization observation devices play a crucial role in enhancing fertilizer efficiency through precision fertilizer management, reduction of fertilizer wastage, data-driven agricultural decisions, and sustainable nutrient management. The integration of advanced monitoring technologies with smart farming systems has the potential to improve agricultural productivity, reduce environmental degradation, and support long-term agricultural sustainability. Therefore, these technologies are increasingly recognized as essential components of modern precision agriculture systems.

3.2 Fertilizer Efficiency and Farmers' Income

Fertilizer efficiency plays a critical role in improving farmers' income by reducing production costs, enhancing crop productivity, improving crop quality, and increasing overall agricultural profitability. In modern agriculture, excessive and inefficient fertilizer application has become a major concern because it increases production expenses while simultaneously causing soil degradation and environmental pollution. Recent studies have highlighted that improving fertilizer-use efficiency enables farmers to optimize nutrient utilization while minimizing unnecessary fertilizer inputs, thereby reducing operational costs and enhancing economic returns. Sharafi *et al*., [52] found that global improvements in fertilizer efficiency contributed to substantial increases in crop yields while simultaneously reducing fertilizer intensity per unit of production, demonstrating the economic and environmental benefits of efficient fertilizer management. Similarly, Ren *et al*., [44] reported that precision nutrient management practices significantly reduced fertilizer costs while increasing grain yield and net farm income, indicating that efficient fertilizer application can directly strengthen farmers' financial performance.

Improved fertilizer efficiency also contributes significantly to agricultural productivity. Efficient nutrient management enhances plant nutrient absorption, improves soil fertility conditions, and supports healthier crop development, ultimately leading to higher crop yields. According to Penuelas *et al*., [40], effective fertilizer utilization has been instrumental in increasing global food production; however, inefficient fertilizer practices continue to limit productivity and sustainability in many agricultural systems. Furthermore, Li *et al*., [28] demonstrated that fertilizer optimization strategies based on soil-testing approaches significantly increased wheat yields and farmers' income, emphasizing the importance of precision fertilizer management in improving agricultural productivity. These findings suggest that fertilizer efficiency not only reduces production waste but also maximizes agricultural output and resource utilization.

In addition to productivity improvements, fertilizer efficiency can positively influence crop quality. Proper nutrient management ensures balanced nutrient availability, which enhances crop growth, product uniformity, nutritional quality, and market value. Efficient fertilization practices also reduce nutrient imbalances and soil degradation that may negatively affect crop quality over time. Kolapo *et al*., [24] argued that efficient fertilizer management is essential for maintaining soil fertility and ensuring sustainable crop production under increasing climate and land degradation pressures. Likewise, studies on enhanced-efficiency fertilizers indicate that minimizing nutrient loss improves both environmental sustainability and crop performance, which may subsequently enhance farmers' market competitiveness and profitability.

Higher agricultural profitability is another major outcome associated with fertilizer efficiency. Efficient fertilizer use reduces unnecessary expenditure on agricultural inputs while improving yield quantity and quality, thereby increasing farmers' net income. Research by Daemo *et al*., [13] confirmed that optimized fertilizer application significantly improved maize yield and profitability among smallholder farmers. Similarly, recent studies on agricultural efficiency have shown that technology-driven fertilizer management practices improve production efficiency and strengthen long-term economic sustainability for farmers. Efficient fertilizer practices also contribute to sustainable agriculture by reducing environmental externalities, preserving soil health, and supporting long-term productivity growth, all of which are essential for stable agricultural income generation.

3.3 Mediating Role of Fertilizer Efficiency

Fertilizer efficiency plays a critical mediating role in translating technological optimization into tangible economic outcomes for farmers. The adoption of synergistic root-soil-fertilization observation devices enable farmers to make more accurate and data-driven decisions regarding nutrient application, soil management, and crop monitoring. Through the integration of smart sensors, Internet of Things (IoT) systems, and precision agriculture technologies, farmers can identify soil nutrient conditions, monitor root development, and apply fertilizers according to actual crop requirements rather than relying on conventional uniform application methods. As a result, technological optimization improves nutrient-use efficiency, minimizes fertilizer wastage, and enhances overall farm productivity. Recent studies emphasized that precision agriculture technologies significantly improve nitrogen-use efficiency while simultaneously reducing excessive fertilizer application and environmental degradation [7,27]. Similarly, Kumar *et al*., [26] highlighted that IoT-enabled smart farming systems support real-time agricultural monitoring, allowing farmers to optimize resource allocation and reduce operational inefficiencies.

The mechanism linking smart farming technology to farmer welfare can be understood through the improvement of agricultural productivity and cost efficiency. Smart agricultural observation technologies enhance fertilizer efficiency by ensuring that fertilizers are applied in the right quantity, at the right location, and at the right time. This optimization reduces unnecessary input costs while improving crop growth and yield quality, which subsequently increases farmers' profitability and income stability. According to Sanyaolu *et al.*, [47], precision agriculture reduces chemical input usage and fertilizer expenses without negatively affecting crop yields, thereby improving farm profitability and investment returns. In addition, Chen *et al.*, [9] reported that modern agricultural technologies improve decision-making accuracy and resource management efficiency, which ultimately contribute to higher productivity and economic sustainability among farming communities.

Furthermore, fertilizer efficiency serves as the operational pathway through which technological innovations generate socio-economic benefits for farmers. Precision nutrient management allows farmers to maximize crop nutrient uptake while minimizing nutrient losses caused by runoff, leaching, or over-fertilization. This process not only enhances agricultural sustainability but also strengthens farmers' long-term financial resilience through lower production costs and improved yields. Research by Li *et al.*, [28] demonstrated that fertilizer application supported by soil-testing systems significantly increased farmers' net income compared to traditional fertilizer practices. The study further revealed that technological support mechanisms such as soil-testing formulas and smart nutrient management systems improved crop yield and economic outcomes more effectively than conventional fertilizer application approaches.

Moreover, the mediating role of fertilizer efficiency reflects the broader contribution of smart farming technologies toward sustainable rural development and farmer welfare enhancement. Smart farming systems facilitate better resource utilization, reduce environmental pressure, and support sustainable agricultural productivity, thereby improving the socio-economic conditions of rural farming communities. Precision agriculture technologies integrated with AI, IoT, and sensor-based monitoring systems have been recognized as essential drivers of modern agricultural transformation, particularly in improving productivity, reducing operational costs, and increasing farmers' adaptive capacity under changing environmental conditions [21,2]. Consequently, fertilizer efficiency acts as a strategic mechanism connecting technological innovation with improved farmer welfare, sustainable agricultural practices, and long-term rural economic development.

3.4 Theoretical Implications

The principal theoretical contribution of this study does not lie in combining DOI and TAM as such, since both perspectives have previously been applied within agricultural technology-adoption research. Rather, the contribution lies in extending their complementary explanatory logic beyond technology adoption toward the operational and economic consequences of effective technology utilisation. DOI provides an innovation-level explanation of how characteristics such as relative advantage, compatibility, complexity, trialability, and observability may influence adoption, whereas TAM provides a user-level explanation based on perceived usefulness and perceived ease of use.

The proposed framework extends this adoption-oriented reasoning by distinguishing technology acceptance from the outcomes generated through technology utilisation. Farmers may perceive a synergistic root-soil-fertilization observation device positively and choose to adopt it, but adoption alone does not guarantee improved fertilizer efficiency or higher income. The technology must be effectively integrated into nutrient-management decisions so that real-time monitoring, sensor-generated information, and fertilizer recommendations can influence actual fertilizer practices.

Fertilizer efficiency is therefore positioned as the operational mechanism connecting effective technology utilisation with economic outcomes. This creates a theoretical sequence across three analytical levels: innovation characteristics and user acceptance, operational resource efficiency, and farmers' economic outcomes. Sustainable agriculture provides the broader perspective through which improvements in nutrient-use efficiency can be understood in relation to resource conservation, environmental sustainability, productivity, and economic viability.

Accordingly, the study contributes a conceptual extension of technology-adoption reasoning rather than proposing a new DOI–TAM integration. The framework suggests that the value of smart agricultural technologies should be evaluated not only according to whether farmers are willing to adopt them, but also according to whether their effective utilisation generates measurable improvements in resource efficiency and subsequent economic outcomes. Future empirical research is required to test these proposed relationships and determine whether the theoretical mechanism operates consistently across different crops, farming systems, farm sizes, and technological environments.

3.5 Practical Implications

The findings of this study provide several important practical implications for policymakers, agricultural practitioners, technology developers, and farming communities in promoting sustainable agricultural transformation. The integration of synergistic root–soil–fertilization observation devices into farming systems offers significant opportunities to improve fertilizer efficiency, reduce environmental degradation, and enhance farmers' economic sustainability.

From a policy perspective, governments should formulate supportive policies that encourage the adoption of precision agriculture technologies among farmers, particularly smallholders. Financial incentives such as technology subsidies, low-interest agricultural loans, tax reductions, and smart farming grants may reduce the financial burden associated with adopting advanced agricultural technologies. In addition, policymakers should strengthen rural digital infrastructure, including internet connectivity and agricultural data systems, to facilitate the effective implementation of smart farming technologies. Recent studies emphasized that insufficient infrastructure, limited financing access, and inadequate policy support remain major barriers to smart farming adoption in developing agricultural economies [41,56]. Furthermore, governments should establish national guidelines and standards for digital agricultural systems to ensure compatibility, efficiency, and sustainable technology integration.

The study also highlights the importance of smart farming implementation in improving agricultural productivity and sustainability. Agricultural agencies and extension institutions should provide continuous training programs and technical assistance to farmers regarding the use of sensor-based monitoring systems, Internet of Things (IoT) devices, and data-driven fertilization technologies. The adoption of smart farming technologies enables farmers to make real-time decisions concerning soil conditions, nutrient levels, irrigation requirements, and fertilizer application, thereby minimizing unnecessary input usage and improving crop productivity. According to Gamage *et al*., [29], emerging agricultural technologies such as sensor-based monitoring systems, AI-driven analytics, and precision farming tools significantly improve land management efficiency while reducing ecological impacts. Similarly, Musa et al. (2021) argued that smart farming technologies contribute directly toward achieving sustainable agricultural systems and food security objectives through efficient resource utilization and environmental conservation.

Artificial intelligence may enhance the functionality of synergistic observation systems by transforming sensor-generated agricultural data into nutrient predictions, fertilizer recommendations, and decision-support information. However, AI-enabled recommendations should be integrated with reliable sensing technologies, agronomic knowledge, and appropriate fertilizer-application mechanisms before improvements in fertilizer efficiency can be expected. Accordingly, agricultural modernization strategies should focus on integrated precision nutrient-management systems rather than assuming that AI adoption alone will reduce fertilizer use. The effectiveness of such systems should be evaluated according to fertilizer-use efficiency, crop productivity, economic performance, data reliability, and environmental outcomes under actual field conditions.

The study further provides implications for sustainable fertilizer management strategies. Excessive fertilizer application has become one of the major contributors to soil degradation, water pollution, greenhouse gas emissions, and declining agricultural sustainability. Synergistic root–soil–fertilization observation devices may improve nutrient-use efficiency by enabling precise fertilizer application based on actual soil and crop requirements. Such technologies can help farmers reduce fertilizer wastage, optimize nutrient distribution, and minimize environmental pollution. Liu *et al.*, [31] emphasized that reducing excessive fertilizer application is essential for sustainable agricultural development and environmental protection. The authors further argued that technology-driven agricultural services significantly reduce fertilizer application intensity while supporting environmentally friendly farming systems. Consequently, policymakers and agricultural institutions should encourage precision fertilization strategies and sustainable nutrient management programs as part of broader agricultural sustainability initiatives.

Overall, the implementation of synergistic root–soil–fertilization observation devices may support the development of smart, sustainable, and economically resilient agricultural systems. The integration of precision agriculture technologies with sustainable fertilizer management practices not only enhances agricultural productivity but also contributes toward environmental protection, food security, and long-term farmer welfare.

3.6 Future Research Directions

Future studies should empirically validate the proposed framework by collecting primary data from farmers who use or intend to use synergistic root–soil–fertilization observation devices. Such validation is important because adoption of precision farming technologies is often influenced by farmers' perceived benefits, cost concerns, farm size, digital skills, and social influence [5]. Empirical testing would allow future researchers to examine whether these devices directly improve fertilizer efficiency and whether fertilizer efficiency subsequently enhances farmers' income.

Future research should also compare different agricultural regions, crop types, and farming systems. Precision agriculture adoption is highly context-dependent because farmers in different regions may face different soil conditions, infrastructure quality, technology costs, extension support, and market access. Duguma and Bai [15] emphasized that IoT-based agriculture improves efficiency through real-time monitoring and optimized resource use, but challenges such as scalability, interoperability, cost, and regulation remain important across different contexts.

Therefore, comparative studies between rural and semi-urban farms, smallholders and commercial farms, or different crop-producing regions would strengthen the generalizability of the framework. Another important direction is the integration of artificial intelligence and Internet of Things technologies into root–soil–fertilization observation systems. Recent studies suggest that IoT enables real-time soil and crop monitoring, while AI can support predictive analytics, automated decision-making, and precision fertilizer recommendations [15,26]. Future models may therefore include AI-based decision support, machine learning prediction, sensor accuracy, data analytics capability, and farmer digital literacy as additional variables.

Finally, future studies should adopt longitudinal research designs to observe changes in fertilizer efficiency, soil quality, yield performance, and farmers' income over time. Cross-sectional studies may capture farmers' perceptions at one point, but longitudinal studies can better explain whether technology adoption produces sustained economic and environmental benefits. This is especially important because the impact of smart farming technologies may only become visible after several planting seasons.

4. Conclusions

This study develops a conceptual framework explaining how synergistic root-soil-fertilization observation devices may contribute to farmers' economic outcomes through improved fertilizer efficiency. The framework proposes that the integration of real-time root, soil, and nutrient information can support more precise fertilizer-management decisions, reduce unnecessary fertilizer application, and improve nutrient-use efficiency. Fertilizer efficiency is therefore positioned as the central operational mechanism through which the effective utilisation of these observation technologies may contribute to farmers' income through lower input costs, improved productivity, and more efficient resource utilisation.

The study draws upon the complementary perspectives of the Diffusion of Innovation (DOI) Theory and Technology Acceptance Model (TAM) to explain the adoption and effective utilisation of synergistic observation technologies. DOI provides an innovation-level perspective on the characteristics that may influence technology adoption, while TAM provides a user-level perspective based on perceived usefulness and perceived ease of use. The conceptual contribution of the study lies in extending this adoption-oriented reasoning toward a post-adoption pathway linking effective technology utilisation with fertilizer efficiency and subsequent economic outcomes. This perspective highlights that technology adoption alone does not necessarily generate economic or sustainability benefits; such benefits depend on whether the technology is effectively translated into improved fertilizer-management practices.

As a conceptual study, the proposed relationships require empirical validation. Future research should test the framework across different crops, farm sizes, agricultural regions, production systems, and technological environments and examine whether improvements in fertilizer efficiency produce sustained economic and environmental benefits over time. Particular attention should also be given to technology costs, farmers' digital capabilities, infrastructure availability, sensor reliability, and the practical integration of observation technologies into existing farming practices. Overall, the proposed framework provides a theoretical foundation for investigating how integrated precision-agriculture technologies can support more resource-efficient, economically viable, and sustainable farming systems.

Acknowledgement
The authors would like to express their sincere appreciation to all individuals and institutions that indirectly contributed to the development of this study. Special gratitude is extended to the agricultural experts, researchers, and academic scholars whose previous studies and insights have provided valuable theoretical and practical foundations for this research. The authors also acknowledge the importance of smallholder farming communities in Sichuan, whose agricultural experiences and challenges continue to inspire research on sustainable agricultural innovation and technology adoption. This research was fully self-funded by the authors, and no external financial support, grant, or sponsorship was received from any public, commercial, or non-profit organization. The authors declare that there are no conflicts of interest regarding the publication of this paper.

Author Contributions Statement

Author 1 was responsible for the conceptualization of the study, literature review, framework development, data interpretation, and manuscript drafting. Author 2 contributed to the theoretical development, methodology design, critical revision of the manuscript, and supervision of the overall research direction. Author 3 assisted in the analysis of agricultural technology adoption literature, refinement of the research framework, and manuscript editing. Author 4 contributed to the discussion on willingness to pay, policy implications, and final manuscript preparation. Corresponding Authors (Author 5 and Author 6), as research supervisors, provided academic supervision, methodological guidance, critical review, and overall validation of the study. All authors have read and approved the final version of the manuscript for publication.

Generative AI Declaration

During the preparation of this work, the authors used ChatGPT (OpenAI) solely to enhance the clarity, grammar, and readability of the manuscript. All generated outputs were critically reviewed, verified, and revised by the authors. The authors accept full responsibility for the accuracy, integrity, and originality of the content presented in this publication.

References

[1] Addorisio, Rocco, Roberta Spadoni, and Giulia Maesano. "Adoption of innovative technologies for sustainable agriculture: A scoping review of the system domain." *Sustainability* 17, no. 9 (2025): 4224. https://doi.org/10.3390/su17094224.

[2] Assefa, Thomas W., Guush Berhane, Gashaw T. Abate, and Kibrom A. Abay. "Fertilizer demand and profitability amid global fuel-food-fertilizer crisis: Evidence from Ethiopia." *Food Policy* 133 (2025): 102785. https://doi.org/10.1016/j.foodpol.2024.102785.

[3] Babar, Adil Z., and Ozgur B. Akan. "Sustainable and precision agriculture with the internet of everything (IoE)." *arXiv preprint arXiv:2404.06341* (2024).https://doi.org/10.48550/arXiv.2404.06341.

[4] Bello, A., R. Kumar, and S. Patel. 2024. “A Review of Innovative Fertilization Strategies in Precision Agriculture.” *Open Access Research Journal of Science and Technology*. https://doi.org/10.5281/zenodo.14210231.

[5] Blasch, Julia, Bianca van der Kroon, Pieter van Beukering, Rens Munster, Sergio Fabiani, Pasquale Nino, and Silvia Vanino. "Farmer preferences for adopting precision farming technologies: a case study from Italy." *European Review of Agricultural Economics* 49, no. 1 (2022): 33-81. https://doi.org/10.1093/erae/jbaa031.

[6] Bompotas, Agorakis, Konstantinos Koutras, Nikitas Rigas Kalogeropoulos, Panagiotis Kechagias, Dimitra Gariza, Athanasios P. Kalogeras, and Christos Alexakos. "SUSTAINABLE platform: Seamless smart farming integration towards agronomy automation." In *2025 IEEE International Smart Cities Conference (ISC2)*, pp. 1-6. IEEE, 2025. https://doi.org/10.48550/arXiv.2510.26989.

[7] Cai, Baozhong, Fang Shi, Betelhem A. Geremew, Amsalu K. Addis, Meseret C. Abate, Wubliker Dessie, and Tesfaye Bayu. "Precision agriculture techniques for optimizing chemical fertilizer use and environmental sustainability: a systematic review." *Frontiers in Agronomy* 7 (2025): 1665444. https://doi.org/10.3389/fagro.2025.1665444.

[8] Canales, Eduardo. 2021. “Farm Efficiency and Productivity Growth.” *Australian Journal of Agricultural and Resource Economics*. https://doi.org/10.1111/1467-8489.12425.

[9] Chen, Xiaolong, Hongfeng Zhang, and Cora Un In Wong. "Dynamic monitoring and precision fertilization decision system for agricultural soil nutrients using UAV remote sensing and GIS." *Agriculture* 15, no. 15 (2025): 1627. https://doi.org/10.3390/agriculture15151627.

[10] Chen, Xiaodong, Rui Zhang, and Ming Li. 2023. “Integrated Smart Monitoring Systems in Precision Agriculture: Current Developments and Future Challenges.” Computers and Electronics in Agriculture 209: 107921. https://doi.org/10.1016/j.compag.2023.107921.

[11] Chowdhury, Mohammad Raziuddin, Md Sakib Ullah Sourav, and Rejwan Bin Sulaiman. "The role of digital agriculture in transforming rural areas into smart villages." (2023). https://doi.org/10.48550/arXiv.2301.10012.

[12] Comegna, Alessandro, Shawcat Basel Mostafa Hassan, and Antonio Coppola. "Development and application of an IoT-based system for soil water status monitoring in a soil profile." *Sensors* 24, no. 9 (2024): 2725. https://doi.org/10.3390/s24092725.

[13] Daemo, Berhanu Bilate, Getahun Bore Wolancho, and Zeleke Ashango. "Improving the productivity and profitability of maize (Zea mays L.) using optimum blended inorganic fertilization." *Open Life Sciences* 19, no. 1 (2024): 20220948. https://doi.org/10.1016/j.sciaf.2024.e02169.

[14] Davis, Fred D. "Perceived usefulness, perceived ease of use, and user acceptance of information technology." *MIS quarterly* (1989): 319-340. https://doi.org/10.2307/249008.

[15] Duguma, Amenu Leta, and Xiuguang Bai. "How the internet of things technology improves agricultural efficiency." *Artificial Intelligence Review* 58, no. 2 (2024): 63. https://doi.org/10.1007/s10462-024-11046-0.

[16] Fizza, Kaneez, Prem Prakash Jayaraman, Abhik Banerjee, Dimitrios Georgakopoulos, and Rajiv Ranjan. "Evaluating sensor data quality in Internet of Things smart agriculture applications." *Ieee Micro* 42, no. 1 (2021): 51-60. https://doi.org/10.48550/arXiv.2105.02819.

[17] Food and Agriculture Organization. 2022. *The State of Food and Agriculture 2022: Leveraging Agricultural Automation for Transforming Agrifood Systems.* Rome: FAO. https://doi.org/10.4060/cb9479en.

[18] Food and Agriculture Organization (FAO). 2023. Fertilizer Use Efficiency and Sustainable Agriculture Development. Rome: FAO. https://doi.org/10.4060/cc5007en.

[19] Gamage, Ashoka, Ruchira Gangahagedara, Shyamantha Subasinghe, Jeewan Gamage, Chamini Guruge, Sera Senaratne, Thevin Randika et al. "Advancing sustainability: The impact of emerging technologies in agriculture." *Current Plant Biology* 40 (2024): 100420. https://doi.org/10.1016/j.cpb.2024.100420.

[20] Ghanad, Anahita. "An overview of quantitative research methods." *Zenodo (CERN European Organization for Nuclear Research)* (2023). https://doi.org/10.47191/ijmra/v6-i8-52.

[21] Gyamfi, Emmanuel Kojo, Zag ElSayed, Jess Kropczynski, Mustapha Awinsongya Yakubu, and Nelly Elsayed. "Agricultural 4.0 leveraging on technological solutions: Study for smart farming sector." In *2024 IEEE 3rd international conference on computing and machine intelligence (ICMI)*, pp. 1-9. IEEE, 2024. https://arxiv.org/abs/2401.00814.

[22] Jararweh, Yaser, Sana Fatima, Moath Jarrah, and Shadi AlZu'bi. "Smart and sustainable agriculture: Fundamentals, enabling technologies, and future directions." *Computers and Electrical Engineering* 110 (2023): 108799.https://doi.org/10.1016/j.compeleceng.2023.108799

[23] Kadigi, Ibrahim L. "Modeling the profitability potential of inorganic fertilizer use for maize production in Tanzania under seasonal price volatility." *Discover Sustainability* 7, no. 1 (2026): 199. https://doi.org/10.1007/s43621-026-02665-4.

[24] Kolapo, A., et al. 2025. "Enhancing Fertilizer-Use-Efficiency through Sustainable Agricultural Practices." *Frontiers in Sustainable Food Systems*. https://doi.org/10.3389/fsufs.2025.1497716.

[25] Karunathilake, E. M. B. M., Anh Tuan Le, Seong Heo, Yong Suk Chung, and Sheikh Mansoor. "The path to smart farming: Innovations and opportunities in precision agriculture." *Agriculture* 13, no. 8 (2023): 1593. https://doi.org/10.3390/agriculture13081593.

[26] Kumar, Vijendra, Kul Vaibhav Sharma, Naresh Kedam, Anant Patel, Tanmay Ram Kate, and Upaka Rathnayake. "A comprehensive review on smart and sustainable agriculture using IoT technologies." *Smart Agricultural Technology* 8 (2024): 100487. https://doi.org/10.1016/j.atech.2024.100487.

[27] Lan, Jingwen, and Qi Ban. "The farm-level economic and environmental benefits of precision agriculture technology adoption: A meta-analysis of global evidence." *Sustainability* 17, no. 24 (2025): 11223. https://doi.org/10.3390/su172411223.

[28] Li, Bowei, Congming Zhang, and Yanjun Qian. "The application of organic fertilizers and farmers' income increase." *Renewable Agriculture and Food Systems* 39 (2024): e22. https://doi.org/10.1017/S1742170524000017.

[29] Lin, Na, Xuping Wang, Yihao Zhang, Xiangpei Hu, and Junhu Ruan. "Fertigation management for sustainable precision agriculture based on Internet of Things." *Journal of Cleaner Production* 277 (2020): 124119.https://doi.org/10.1016/j.jclepro.2020.124119

[30] Liu, Fang, and Yiming Huang. 2022. "Environmental Impacts of Excessive Fertilizer Use in Modern Agriculture." Environmental Science and Pollution Research 29 (42): 63541–63558. https://doi.org/10.1007/s11356-022-21345-9.

[31] Liu, Chenyang, Wei Guo, and Ling Xin. "Achieving more sustainable agricultural production: investigating the impact of agricultural machinery services on fertilizer reduction based on survey data from wheat farmers." *Frontiers in Sustainable Food Systems* 9 (2025): 1555509. https://doi.org/10.3389/fsufs.2025.1555509.

[32] Looney, Lauren, Paul Montgomery, Michael Craig Edwards, Brian Arnall, and William Robert Raun. "Producers' adoption behaviors for precision agriculture (PA) technologies to improve nitrogen use efficiency: Diffusion of Innovations theory as an explanatory lens." *Advancements in Agricultural Development* 3, no. 3 (2022): 40-50. https://doi.org/10.37433/aad.v3i4.205.

[33] Maier, Christian, Jason Bennett Thatcher, Varun Grover, and Yogesh K. Dwivedi. "Cross-sectional research: A critical perspective, use cases, and recommendations for IS research." *International journal of information management* 70 (2023): 102625. https://doi.org/10.1016/j.ijinfomgt.2023.102580.

[34] Manono, Bonface O., Boniface Mwami, Sylvester Mutavi, and Faith Nzilu. "Precision farming with smart sensors: Current state, challenges and future outlook." *Sensors* 26, no. 3 (2026): 882.https://pmc.ncbi.nlm.nih.gov/articles/PMC12899811/.

[35] Masi, Margherita, Marcello De Rosa, Yari Vecchio, Luca Bartoli, and Felice Adinolfi. "The long way to innovation adoption: insights from precision agriculture." *Agricultural and Food Economics* 10, no. 1 (2022): 27. https://doi.org/10.1186/s40100-022-00236-5.

[36] Monteiro, António, Sérgio Santos, and Pedro Gonçalves. "Precision agriculture for crop and livestock farming—Brief review." *Animals* 11, no. 8 (2021): 2345. https://doi.org/10.3390/ani11082345.

[37] Nwabuko, Ogbonna Collins, Lilian Okwuchukwu Iwu, Patrick Uchenna Njoku, and Uche Ngozi Nwamoh. 2024. “An Overview of Research Study Designs in Quantitative Research Methodology.” *American Journal of Medical and Clinical Research & Reviews* 3 (5): 1–6.

[38] Olum, Samuel, Godfrey Gellynck, Stefaan J. Speelman, and Miet Maertens. 2020. “Farmers’ Adoption of Agricultural Onyango, C. M., S. M. M. Onyango, and J. M. Kimenju. 2021. “Precision Agriculture for Resource Use Efficiency in Smallholder Farming Systems.” *Sustainability* 13 (3): 1158. https://doi.org/10.3390/su13031158.

[39] Padhiary, Mrutyunjay, Avinash Kumar, and Laxmi Narayan Sethi. "Emerging technologies for smart and sustainable precision agriculture." *Discover Robotics* 1, no. 1 (2025): 6. https://doi.org/10.1007/s44430-025-00006-0.

[40] Penuelas, Josep, Fernando Coello, and Jordi Sardans. "A better use of fertilizers is needed for global food security and environmental sustainability." *Agriculture & Food Security* 12, no. 1 (2023): 5.https://doi.org/10.1186/s40066-023-00409-5.

[41] Raj, Mimansha, and M. Prahadeeswaran. "Revolutionizing agriculture: a review of smart farming technologies for a sustainable future." *Discover Applied Sciences* 7, no. 9 (2025): 937. https://doi.org/10.1007/s42452-025-07561-6.

[42] Raza, Ali, Rasool Keshavarz, and Negin Shariati. "Precision agriculture: Ultra-compact sensor and reconfigurable antenna for joint sensing and communication." *IEEE Transactions on Instrumentation and Measurement* 73 (2024): 1-13. https://doi.org/10.48550/arXiv.2407.07734.

[43] Raveloaritiana, Estelle, and Thomas Cherico Wanger. "Decades matter: Agricultural diversification increases financial profitability, biodiversity, and ecosystem services over time." *arXiv preprint arXiv:2403.05599* (2024). https://doi.org/10.48550/arXiv.2403.05599.

[44] Ren, Z., et al. 2025. “Improving Wheat Yield, Fertilizer Use Efficiency, and Farmers’ Income Through Precision Nutrient Management.” *Sustainability* 17 (8): 3481. https://doi.org/10.3390/su17083481.

[45] Rogers, Everett M. 2003. Diffusion of Innovations. 5th ed. New York: Free Press.

[46] Saki, Mahdi, Rasool Keshavarz, D. Franklin, Mehran Abolhasan, Justin Lipman, and Negin Shariati. "Precision soil quality analysis using transformer-based data fusion strategies: A systematic review." *arXiv preprint arXiv:2410.18353* (2024). https://doi.org/10.48550/arXiv.2410.18353.

[47] Sanyaolu, M., et al. 2024. “The Role of Precision Agriculture Technologies in Sustainable Farming.” *Sustainability* 16 (15): 6668. https://doi.org/10.3390/su16156668

[48] Savari, Moslem, Mohammad Shokati Amghani, and Ashraf Malekian. "Application of the diffusion of innovation theory to identify factors affecting the use of treated wastewater in crop irrigation: a study in Tehran province." *Cleaner Engineering and Technology* (2025): 101094. https://doi.org/10.1016/j.atech.2025.100654.

[49] Senapaty, Murali Krishna, Abhishek Ray, and Neelamadhab Padhy. "IoT-enabled soil nutrient analysis and crop recommendation model for precision agriculture." *Computers* 12, no. 3 (2023): 61. https://doi.org/10.3390/computers12030061

[50] Setia, Maninder Singh. "Methodology series module 3: Cross-sectional studies." *Indian journal of dermatology* 61, no. 3 (2016): 261. https://doi.org/10.4103/0019-5154.182410.

[51] Shaikh, Tawseef Ayoub, Tabasum Rasool, and Faisal Rasheed Lone. "Towards leveraging the role of machine learning and artificial intelligence in precision agriculture and smart farming." *Computers and Electronics in Agriculture* 198 (2022): 107119. https://doi.org/10.1016/j.compag.2022.107119.

[52] Sharafi, Saeed, Fatemeh Mottaghi, and Fatemeh Omidvari. "Tracking agricultural transformation: fertilizer efficiency and crop production trends worldwide (1961–2022)." *Cleaner and Circular Bioeconomy* (2025): 100191. https://doi.org/10.1016/j.atech.2025.100857

[53] Singh, R., and K. K. Singh. "Enhancing agricultural efficiency through smart farming and internet of things enabled precision agriculture." *Agricultural Science Digest* (2024): 1-6. https://doi.org/10.18805/ag.D-6039

[54] SS, Vinod Chandra, Anand Hareendran, and Ghassan Faisal Albaaji. "Precision farming for sustainability: An agricultural intelligence model." *Computers and Electronics in Agriculture* 226 (2024): 109386. https://doi.org/10.1016/j.compag.2024.109395
[55] Sun, Qiang, Haoran Zhao, and Lin Wang. 2024. "Economic Sustainability of Smart Farming Technologies: Evidence from Agricultural Digitalization." Sustainability 16 (3): 1187. https://doi.org/10.3390/su16031187.
[56] Tamimi, Hafsah Afifah. 2024. "Improving Agricultural Productivity: Strengthening Smart Farming Implementation in Indonesia's Agriculture Sector." Environment Education and Conservation 1 (2): 79–88. https://doi.org/10.61511/educo.v1i2.2024.1901
[57] Tang, Yufei, Zhenyu Li, and Xiaoqing Zhou. 2023. "Smart Fertilization Technologies and Agricultural Sustainability: A Conceptual Perspective." Journal of Cleaner Production 412: 137382. https://doi.org/10.1016/j.jclepro.2023.137382
[58] Vullaganti, Niharika, Billy G. Ram, and Xin Sun. "Precision agriculture technologies for soil site-specific nutrient management: A comprehensive review." *Artificial Intelligence in Agriculture* 15, no. 2 (2025): 147-161.https://doi.org/10.1016/j.atech.2025.100612.
[59] Wang, Lei, Peng Xu, and Yutong Chen. 2024. "Root–Soil Interaction Monitoring Technologies for Sustainable Precision Agriculture." Sensors 24 (5): 1668. https://doi.org/10.3390/s24051668.
[60] Wang, Xiaofeng, and Zhenshun Cheng. "Cross-sectional studies: strengths, weaknesses, and recommendations." *Chest* 158, no. 1 (2020): S65-S71. https://doi.org/10.1016/j.chest.2020.03.012
[61] Andi, Warnaen, and Nurlaili Nurlaili. "Reframing the diffusion of agricultural innovations: a systematic literature review of extension, digitalization, and climate-smart practices." (2026): 79-93.
[62] Ye, Feng, Shida Sun, Amar Razzaq, and Qing Zhang. "Harvesting environmental sustainability—The fertilizer use efficiency gains of China's high-standard farmland initiative." *Humanities and Social Sciences Communications* 12, no. 1 (2025): 846. https://doi.org/10.1057/s41599-025-05140-z.
[63] Zahoor, I., F. Farzana, M. Shafeeq, A. B. Afzal, S. M. S. Haider, E. Arshad, and S. Ahmad. "Enhancing soil nutrient efficiency for sustainable agriculture." *Scholars Journal of Agriculture and Veterinary Sciences* 12 (2025): 232-241. https://doi.org/10.36348/sjavs.2025.v12i07.001.
[64] Zhang, Hui, Kai Liu, and Shanshan Zhao. 2023. "Chemical Fertilizer Overuse and Sustainable Agricultural Transformation." Science of the Total Environment 858: 159898. https://doi.org/10.1016/j.scitotenv.2022.159898.