SARJANA INTELEK PUBLISHING
PUBLISHING THE FUTURE TODAY

Sarjana International Journal of Sustainable Food and Agriculture

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

The Role of Multi-Source Information Fusion Smart Agricultural Integration Platforms in Enhancing Agricultural Efficiency and Regional Adaptation

Yutan Chen[1], Weijie Song[1], Weijie Song[1], Wenying Zhai[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:
Smart agriculture; multi-source information fusion; precision agriculture; agricultural efficiency; regional adaptation; sustainable farming; IoT; artificial intelligence

ABSTRACT

The increasing demand for sustainable and adaptive agriculture has accelerated the adoption of smart farming technologies and digital agricultural systems. This study examines the role of multi-source information fusion smart agricultural integration platforms in enhancing agricultural efficiency and supporting regional agricultural adaptation. Drawing upon the Diffusion of Innovation (DOI) Theory and Technology Acceptance Model (TAM), the study proposes a framework linking integrated agricultural information systems, agricultural efficiency, and regional adaptation outcomes. The study highlights the importance of artificial intelligence (AI), Internet of Things (IoT), remote sensing, and real-time analytics in improving precision farming, operational efficiency, and sustainable agricultural resilience. The findings are expected to provide valuable implications for policymakers, researchers, agricultural technologists, and farming communities in promoting sustainable smart agriculture development.

1. Introduction

The global agricultural sector is currently facing significant sustainability challenges driven by rapid population growth, climate change, environmental degradation, resource scarcity, and increasing food demand. Modern agriculture is under pressure to improve productivity while simultaneously reducing environmental impacts and ensuring long-term food security. Traditional farming systems often rely heavily on excessive water consumption, chemical fertilizers, pesticides, and labor-intensive practices, which contribute to soil degradation, greenhouse gas emissions, biodiversity loss, and declining agricultural resilience. Recent studies highlighted that sustainable agricultural transformation has become essential for balancing food production, environmental protection, and economic stability in response to global agricultural pressures [16,27]. Smart farming and digital agriculture technologies are increasingly recognized as important solutions for addressing

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

these sustainability challenges through resource optimization, data-driven decision-making, and operational efficiency improvements.

Climate change has further intensified agricultural uncertainties across different regions by increasing temperature variability, irregular rainfall patterns, drought frequency, flooding, pest outbreaks, and crop diseases. These environmental changes have significantly affected crop productivity, soil conditions, and farming stability, particularly in climate-sensitive agricultural regions. As a result, regional agricultural adaptation has become a major priority in ensuring resilient and sustainable food production systems. Recent studies reported that digital agriculture technologies, including artificial intelligence (AI), Internet of Things (IoT), remote sensing, climate analytics, and precision agriculture systems, can support climate adaptation through predictive analytics, real-time monitoring, and adaptive farm management strategies [29,33].These technologies enable farmers and agricultural stakeholders to respond more effectively to environmental changes while improving resource-use efficiency and agricultural resilience.

In response to these challenges, the demand for digital transformation in agriculture has increased substantially over the past decade. The emergence of Agriculture 4.0 has accelerated the integration of advanced technologies such as AI, machine learning, IoT, cloud computing, geographic information systems (GIS), satellite imaging, drones, and big data analytics into agricultural operations. These technologies facilitate precision farming, automated monitoring, predictive modeling, and intelligent decision-support systems that improve agricultural productivity and operational management. Recent studies emphasized that digital agriculture contributes significantly toward reducing production costs, minimizing resource wastage, enhancing productivity, and supporting sustainable farming systems [21,38]. Furthermore, digital agricultural transformation allows farmers to optimize irrigation, fertilization, disease management, and crop monitoring through real-time information systems and intelligent analytics.

Despite these advancements, conventional agricultural management systems continue to face several limitations, particularly in handling complex agricultural environments and region-specific farming challenges. Traditional systems often operate using fragmented information sources, delayed decision-making processes, manual monitoring methods, and isolated data management structures. These limitations reduce operational efficiency and restrict farmers' ability to respond effectively to changing environmental conditions. In many cases, agricultural data derived from soil monitoring, weather forecasting, satellite imagery, crop health sensors, and farm operations remain disconnected, resulting in inefficient resource allocation and suboptimal agricultural performance. Previous studies indicated that fragmented agricultural data systems and lack of integration among smart farming technologies remain major barriers to achieving sustainable agricultural digitalization and climate adaptation [17,28].

Consequently, smart agriculture and multi-source information fusion technologies have emerged as transformative approaches for modern agricultural management. Information fusion technologies integrate data from multiple agricultural sources, including IoT sensors, remote sensing systems, weather databases, drones, satellite imagery, soil sensors, and crop monitoring platforms, into a unified intelligent agricultural management system. Through AI-driven analytics and real-time data processing, these platforms enhance decision-making accuracy, operational coordination, and predictive agricultural management. Recent studies highlighted that multi-source data fusion systems improve predictive modeling, precision farming accuracy, and agricultural sustainability by integrating heterogeneous agricultural datasets into comprehensive smart farming platforms [30].

The importance of multi-source agricultural information integration platforms continues to increase as agriculture becomes more data-intensive and climate-sensitive. Integrated smart agricultural platforms provide farmers, policymakers, and agricultural agencies with real-time insights for crop management, climate adaptation, resource allocation, and productivity optimization. These systems support more adaptive and resilient agricultural practices by enabling predictive analytics, precision resource management, and coordinated agricultural decision-making across different farming regions. Moreover, integrated agricultural information platforms contribute toward sustainable farming by improving efficiency, reducing operational uncertainty, minimizing environmental impacts, and enhancing long-term agricultural resilience. Therefore, the integration of multi-source information fusion technologies into smart agricultural systems represents an important advancement toward sustainable agricultural modernization and regional agricultural adaptation in the era of digital transformation.

1.1 Smart Agriculture and Digital Agricultural Transformation

The rapid advancement of digital technologies has significantly transformed the agricultural sector from conventional farming practices toward precision agriculture and smart farming systems. Precision agriculture emerged as an innovative farming approach aimed at improving agricultural productivity, resource efficiency, and sustainability through the application of advanced technologies such as Global Positioning Systems (GPS), remote sensing, geographic information systems (GIS), and sensor-based monitoring systems. Over time, precision agriculture has evolved into smart agriculture or Agriculture 4.0, which integrates artificial intelligence (AI), Internet of Things (IoT), robotics, cloud computing, big data analytics, and machine learning into agricultural operations to support automated and data-driven farming management [21,40]. The evolution of precision agriculture reflects the growing need to address global food security challenges, climate change, labor shortages, and resource scarcity while improving agricultural efficiency and environmental sustainability.

Smart farming technologies have become increasingly important in modern agricultural systems due to their ability to optimize production processes and improve decision-making efficiency. Smart agriculture utilizes interconnected digital systems, intelligent sensors, drones, satellite imaging, and automated machinery to monitor crop conditions, soil quality, irrigation systems, and environmental changes in real time. These technologies support precision resource allocation, reduce operational inefficiencies, and minimize environmental impacts associated with excessive use of fertilizers, pesticides, and water resources [15,19]. Furthermore, smart farming systems allow farmers to perform predictive agricultural management by identifying crop diseases, weather risks, and soil nutrient deficiencies through intelligent monitoring platforms and automated analytics systems.

Artificial intelligence and big data analytics have also become central components of digital agricultural transformation. AI technologies enable predictive modeling, crop health assessment, automated decision-making, and yield optimization by processing large-scale agricultural datasets collected from multiple sources such as sensors, drones, satellites, and farm management systems. Big data analytics supports farmers and agricultural agencies in analyzing historical and real-time agricultural information to improve productivity, optimize resource utilization, and enhance climate-responsive agricultural planning [2,39]. Recent studies reported that AI-driven agricultural systems improve crop monitoring, automate farming operations, reduce labor dependency, and support sustainable agricultural management through predictive analytics and intelligent recommendations. The integration of AI and big data technologies has therefore accelerated the transition toward highly automated and intelligent agricultural ecosystems.

In addition, IoT-enabled agricultural systems have revolutionized agricultural monitoring and operational management by facilitating real-time communication among agricultural devices, sensors, and digital platforms. IoT technologies allow continuous monitoring of soil moisture, temperature, humidity, crop growth, nutrient levels, irrigation systems, and environmental conditions through interconnected smart sensors and wireless communication networks. The integration of IoT systems with AI and cloud computing technologies enables automated irrigation management, precision fertilization, disease detection, and remote farm supervision. Studies further highlighted that IoT-enabled smart farming improves operational efficiency, reduces resource wastage, and enhances sustainability by enabling data-driven agricultural management and automated agricultural responses [2,19].

The transformation toward data-driven agricultural management represents one of the most significant developments in modern agriculture. Data-driven farming systems rely on the collection, integration, and analysis of agricultural data from multiple digital sources to support accurate and timely decision-making. Smart agricultural platforms combine climate data, crop monitoring systems, sensor information, satellite imagery, and predictive analytics to generate actionable agricultural insights for farmers and policymakers. This integrated digital approach enables precision resource management, adaptive agricultural planning, and sustainable farming operations under changing environmental conditions [2]. Moreover, governments and agricultural institutions worldwide have increasingly promoted agricultural digitalization strategies to strengthen food security, improve productivity, and support sustainable agricultural transformation. For example, China's 2024–2028 Smart Agriculture Action Plan emphasizes the integration of AI, big data, GPS technologies, and digital agricultural platforms to modernize agricultural production systems and enhance national food security.

1.2 Multi-Source Information Fusion Smart Agricultural Platforms

Multi-source information fusion smart agricultural platforms refer to integrated digital agricultural systems that combine heterogeneous agricultural data from multiple sources, including IoT sensors, satellite imagery, climate information systems, drones, farm management software, and artificial intelligence (AI)-based analytics, to support intelligent agricultural monitoring and decision-making. These platforms are designed to enhance agricultural productivity, operational efficiency, sustainability, and adaptive farming practices through real-time data integration and advanced analytical capabilities. Multi-source information fusion enables agricultural systems to combine diverse datasets into unified and meaningful information structures capable of improving precision agriculture and smart farming operations [40]. The increasing complexity of agricultural environments, coupled with climate variability and resource constraints, has accelerated the need for integrated digital agricultural platforms capable of supporting data-driven agricultural management and sustainable farming systems.

The concept of multi-source information fusion in agriculture is closely associated with the integration of sensing technologies, remote sensing systems, environmental monitoring devices, and predictive analytics into unified agricultural intelligence platforms. These systems combine real-time field data collected from soil sensors, weather stations, irrigation systems, crop monitoring devices, and satellite observations to generate comprehensive agricultural insights for farmers and agricultural stakeholders. Recent studies emphasized that information fusion technologies improve agricultural monitoring accuracy, predictive performance, and operational responsiveness by integrating multimodal data sources across agricultural environments. Through multi-source data integration, smart agricultural systems are able to monitor crop health, soil conditions, water usage, climate risks, pest outbreaks, and productivity trends in near real-time, thereby improving agricultural resilience and sustainability.

The integration of sensors, satellite imagery, climate data, and farm management systems represents one of the core foundations of smart agricultural integration platforms. IoT-enabled sensors installed in farms continuously collect environmental and operational data such as soil moisture, temperature, humidity, nutrient levels, irrigation status, and crop growth conditions. Satellite imagery and remote sensing technologies complement field-level sensing systems by providing large-scale spatial monitoring capabilities for crop health analysis, land-use mapping, and climate observation. Climate data systems further enhance predictive agricultural analytics by supplying weather forecasts, rainfall patterns, temperature variability, and extreme climate event monitoring. The integration of these technologies with farm management systems creates comprehensive digital ecosystems capable of supporting precision agriculture and adaptive farming practices. Moreover, integrated agricultural platforms allow farmers to remotely monitor farm conditions, automate irrigation and fertilization systems, and optimize resource allocation through intelligent analytics and real-time operational control.

Real-time agricultural monitoring and analytics constitute another essential component of multi-source information fusion smart agricultural platforms. Smart agricultural systems increasingly rely on AI-driven analytics, cloud computing, edge computing, and machine learning algorithms to process large-scale agricultural data in real time. These technologies enable continuous monitoring of agricultural environments while generating predictive insights related to crop performance, disease detection, irrigation requirements, yield estimation, and environmental risks. Recent research indicated that real-time agricultural analytics significantly improve agricultural efficiency, operational accuracy, and climate-responsive farming management through dynamic decision-support capabilities [40]. In addition, multimodal data fusion approaches have demonstrated substantial potential for improving predictive agricultural intelligence by integrating remote sensing, IoT systems, and climate analytics into unified decision-making frameworks.

Intelligent agricultural decision-support systems further strengthen the functionality of smart agricultural integration platforms by transforming complex agricultural data into actionable farming recommendations. These systems apply AI, machine learning, predictive modeling, and expert-system technologies to support decisions related to irrigation scheduling, fertilizer management, pest control, crop selection, and harvest planning. Intelligent decision-support systems reduce uncertainty in agricultural operations while improving precision farming efficiency and environmental sustainability. Studies suggested that AI-driven agricultural systems contribute significantly toward improving agricultural resilience, optimizing farm operations, and supporting climate-smart agriculture initiatives [3]. Furthermore, integrated agricultural decision-support systems are increasingly being utilized to improve adaptive agricultural strategies under climate change and resource-constrained farming conditions.

Digital integration in smart farming environments has become a major driver of agricultural modernization and sustainable agricultural transformation. Smart agricultural integration platforms facilitate interoperability among agricultural technologies, communication networks, cloud infrastructures, edge computing systems, and farm management applications. This digital integration enables seamless agricultural data exchange, coordinated farm management, and intelligent automation across different agricultural operations. Modern smart farming ecosystems increasingly combine IoT, AI, big data analytics, cloud computing, and remote sensing technologies to establish interconnected agricultural intelligence networks capable of supporting efficient and sustainable farming systems [3,40]. Consequently, multi-source information fusion smart agricultural platforms are becoming essential tools for enhancing agricultural productivity, climate adaptability, operational efficiency, and sustainable agricultural development in modern farming environments.

1.3 Agricultural Efficiency and Sustainable Farming

Agricultural efficiency and sustainable farming have become central priorities in modern agricultural development due to increasing global food demand, climate change pressures, resource scarcity, and environmental degradation. Agricultural efficiency refers to the optimization of agricultural inputs, production processes, and resource utilization to maximize productivity while minimizing waste and environmental impact. Recent advancements in smart agriculture, precision farming, artificial intelligence (AI), Internet of Things (IoT), remote sensing, and data analytics have significantly contributed toward improving agricultural productivity optimization and sustainable farming systems [40].

These technologies enable farmers to make data-driven decisions regarding irrigation, fertilization, pest control, and crop monitoring, ultimately improving operational performance and agricultural sustainability.

One of the major contributions of smart farming technologies is the enhancement of resource-use efficiency. Precision agriculture systems allow accurate monitoring and management of water, fertilizers, pesticides, and energy resources based on real-time environmental and crop conditions. Through the integration of sensors, GPS, satellite imagery, and AI-driven analytics, farmers can optimize the use of agricultural inputs and reduce unnecessary resource consumption. Precision farming technologies have been shown to improve nutrient-use efficiency, reduce water wastage, and optimize land-use management while maintaining high agricultural productivity levels. Furthermore, IoT-enabled smart agriculture systems facilitate continuous monitoring of soil moisture, weather conditions, and crop health, enabling more efficient and adaptive farm management practices [40].

In addition, smart agricultural systems contribute substantially toward cost reduction in farming operations. Traditional agricultural practices often involve excessive use of fertilizers, pesticides, labor, and irrigation resources, resulting in high operational expenses and reduced profitability. Smart farming technologies and precision agricultural platforms enable farmers to automate agricultural processes, improve operational accuracy, and minimize production inefficiencies. Studies have shown that AI-driven smart farming systems and IoT-based agricultural management platforms can reduce operational costs by optimizing resource allocation, minimizing waste, and improving production planning [34]. Precision agricultural systems also support predictive decision-making, helping farmers anticipate environmental changes, pest outbreaks, and irrigation requirements more effectively.

Precision resource allocation is another important element supporting sustainable farming systems. Precision agriculture allows farmers to allocate resources according to the specific needs of crops and field conditions rather than applying uniform treatment across entire farming areas. This targeted approach improves productivity while reducing environmental burden and operational waste. Smart agricultural integration platforms combining IoT devices, AI analytics, drones, and satellite systems provide comprehensive agricultural insights that support highly accurate resource management and precision farming operations [8,11]. As a result, precision resource allocation contributes to more resilient and adaptive agricultural systems capable of responding to climate variability and regional farming challenges.

Environmental sustainability has also become a key objective of smart farming and precision agriculture initiatives. Excessive agricultural input usage and inefficient farming practices have contributed significantly to soil degradation, water pollution, greenhouse gas emissions, and biodiversity loss. Smart agriculture technologies help mitigate these environmental problems by enabling environmentally responsible farming practices and reducing unnecessary chemical applications. Precision agriculture minimizes environmental footprints through optimized fertilizer application, controlled irrigation systems, and efficient pesticide management. Additionally, modern agricultural technologies support sustainable intensification by improving agricultural productivity while preserving natural resources and environmental quality (Chen et al. 2025). Therefore, smart farming systems play an increasingly important role in achieving long-term agricultural sustainability, food security, and climate-resilient farming development.

1.4 Regional Adaptation in Agriculture

Regional adaptation in agriculture has become increasingly important due to the growing impacts of climate change, environmental uncertainty, and regional climate variability on agricultural productivity and food security. Different agricultural regions experience varying levels of temperature fluctuations, rainfall irregularities, drought frequency, flooding, soil degradation, and pest outbreaks, all of which directly affect farming systems and crop performance. Recent studies have shown that climate variability significantly disrupts agricultural productivity and threatens the sustainability of farming communities, particularly in climate-sensitive regions [10]. As climate risks continue to intensify, agricultural systems must become more adaptive and resilient to ensure stable food production and long-term sustainability.

Adaptive agricultural management has therefore emerged as a critical strategy for addressing region-specific agricultural challenges. Adaptive management involves the implementation of flexible, data-driven, and climate-responsive farming practices that enable farmers to respond effectively to changing environmental conditions. Climate-smart agriculture (CSA) approaches emphasize the integration of sustainable farming practices, efficient resource utilization, and technological innovation to improve resilience against climate-related risks [24]. These adaptive strategies include precision irrigation, climate-resilient crop varieties, conservation agriculture, soil health management, and integrated water resource management, all of which support agricultural sustainability and productivity under changing climatic conditions.

In addition, region-specific farming strategies are essential because agricultural adaptation requirements vary significantly across geographical regions, ecological systems, and farming environments. Farming systems in arid regions may prioritize drought-resistant crops and efficient water management, while flood-prone regions may focus on drainage systems, flood-tolerant crops, and climate forecasting technologies. Recent studies emphasized that localized adaptation strategies are more effective because they consider specific environmental, climatic, and socioeconomic conditions faced by farming communities [20,25]. Therefore, agricultural adaptation should not rely solely on generalized approaches but instead incorporate regional agricultural characteristics and local climate conditions to improve resilience and productivity.

Agricultural resilience and sustainability are also central components of regional adaptation in agriculture. Agricultural resilience refers to the ability of farming systems to withstand, recover from, and adapt to environmental disruptions while maintaining productivity and food security. Sustainable agricultural systems promote long-term ecological balance, efficient resource utilization, biodiversity conservation, and economic viability for farming communities. Climate-smart agricultural practices have been recognized as important mechanisms for simultaneously improving productivity, strengthening resilience, and reducing environmental impacts [46]. Moreover, sustainable farming practices such as conservation agriculture, crop diversification, and precision resource management enhance soil quality, water conservation, and climate resilience in agricultural landscapes [23].

Furthermore, smart technologies have become increasingly important in supporting regional agricultural adaptation and climate-resilient farming systems. Technologies such as Internet of Things

(IoT) sensors, artificial intelligence (AI), satellite imagery, remote sensing, predictive analytics, and multi-source information fusion systems provide farmers with real-time environmental data and decision-support capabilities for adaptive agricultural management. Smart agricultural technologies improve precision farming, resource optimization, climate forecasting, and early warning systems, enabling more efficient responses to regional climate variability [11]. In addition, satellite-based monitoring systems and geospatial technologies help identify regional climate risks and optimize agricultural planning and resource allocation. Consequently, the integration of smart technologies into agricultural systems represents a significant advancement toward improving regional adaptation, sustainable farming resilience, and long-term agricultural sustainability.

1.5 Theoretical Foundation

The theoretical foundation of this study integrates the Diffusion of Innovation (DOI) Theory and the Technology Acceptance Model (TAM) to explain the adoption and effective utilisation of multi-source information fusion smart agricultural integration platforms. The integration of these theories is appropriate because smart agricultural technology adoption involves both the characteristics of the technological innovation itself and users' perceptions of its usefulness and usability. Neither perspective alone fully captures these complementary dimensions of technology adoption.

The Diffusion of Innovation (DOI) Theory developed by Rogers (2003) explains how an innovation spreads and is adopted within a social system over time. DOI proposes that adoption is influenced by perceived characteristics of an innovation, particularly its relative advantage, compatibility, complexity, trialability, and observability. Within smart agriculture, these characteristics are particularly relevant because farmers and agricultural stakeholders must evaluate whether integrated digital platforms offer advantages over existing farming practices, are compatible with current agricultural operations, can be understood and implemented without excessive complexity, can be tested before extensive implementation, and produce observable benefits. Previous agricultural technology research has demonstrated the relevance of innovation characteristics such as relative advantage and compatibility in explaining the adoption of precision and smart-farming technologies.

However, DOI primarily explains adoption from the perspective of innovation characteristics and diffusion processes and provides a less specific explanation of the cognitive evaluations through which individual users develop acceptance of an information system. TAM complements this limitation by explaining technology acceptance through two principal beliefs: perceived usefulness and perceived ease of use [14]. Perceived usefulness represents the extent to which users believe that adopting a technology will improve their performance, whereas perceived ease of use concerns the degree to which the technology is perceived as requiring limited effort to operate. In the context of multi-source information fusion platforms, farmers and agricultural stakeholders may therefore evaluate not only the innovative characteristics of the platform but also whether its integrated information, AI-driven analytics, real-time monitoring, and decision-support functions are useful and sufficiently accessible for agricultural operations.

The integration of DOI and TAM consequently provides a more comprehensive theoretical explanation than either theory applied independently. DOI explains how the characteristics of the innovation influence its diffusion and adoption, whereas TAM explains how users cognitively evaluate the usefulness and usability of the technology before accepting and using it. These perspectives are complementary rather than competing. Innovation characteristics identified by DOI can shape users' perceptions represented within TAM. For example, a platform demonstrating clear relative advantage and compatibility with existing agricultural practices may strengthen perceived usefulness, while lower technological complexity may enhance perceived ease of use. Research on smart-farming adoption similarly indicates that technological attributes and users' psychological evaluations interact in shaping technology adoption decisions. More recent research applying integrated DOI–TAM approaches to climate-smart and AI-enabled agriculture further demonstrates the usefulness of combining innovation-level and user-level perspectives when explaining agricultural digitalisation.

Within the present study, DOI and TAM therefore provide the theoretical foundation for explaining how multi-source information fusion platforms can progress from technological innovation to user acceptance and effective utilisation. DOI captures the perceived attributes that encourage agricultural stakeholders to consider and adopt the integrated platform, while TAM explains whether users perceive the platform as useful and sufficiently easy to incorporate into agricultural decision-making. Effective utilisation subsequently enables the technological capabilities of the platform—including data integration, real-time monitoring, AI-driven analytics, IoT connectivity, and decision-support functionality—to be translated into improved agricultural efficiency. Enhanced agricultural efficiency, in turn, provides an operational pathway through which digital agricultural integration can contribute to regional agricultural adaptation.

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

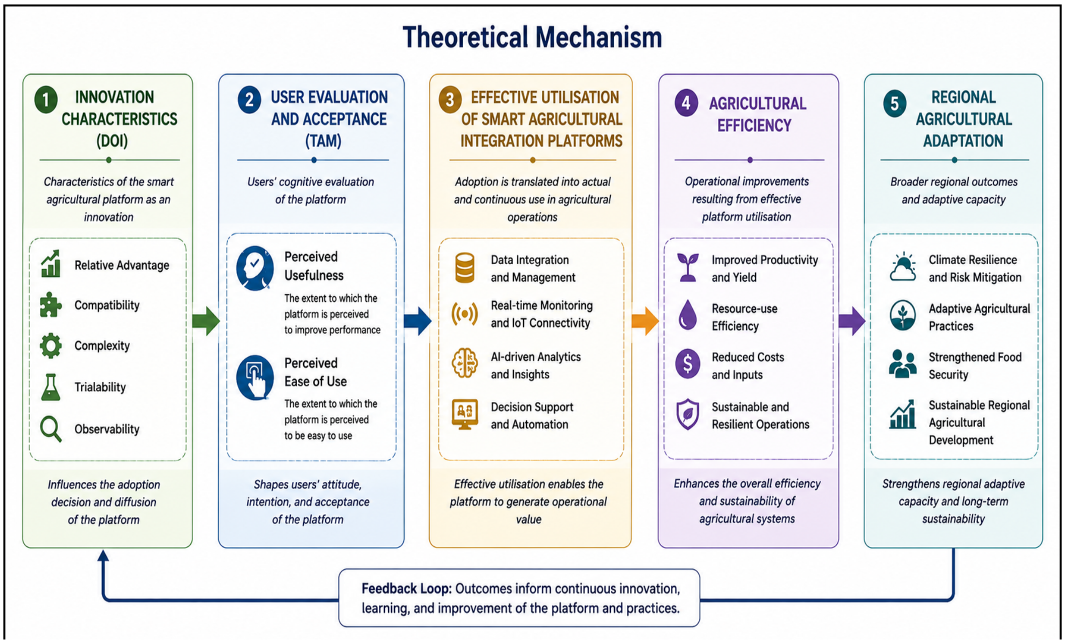

Fig. 1. Theoretical mechanism

This integrated theoretical perspective addresses an important limitation of applying DOI or TAM independently. Rather than treating technology adoption solely as a diffusion process or an individual acceptance decision, the framework conceptualises smart agricultural platform adoption as a sequential process in which innovation characteristics influence users' evaluations, acceptance facilitates effective technological utilisation, and effective utilisation generates operational and adaptive agricultural outcomes.

1.6 Research Gap, Significance, and Objectives

The rapid advancement of smart agriculture technologies, artificial intelligence (AI), Internet of Things (IoT), cloud computing, and big data analytics has significantly transformed agricultural production systems worldwide. Multi-source information fusion technologies have emerged as important tools for integrating various agricultural data sources, including climate data, soil information, remote sensing imagery, sensor networks, and farm management systems, to support precision agriculture and intelligent decision-making processes. Recent studies have emphasized that integrated agricultural information systems contribute to improved agricultural monitoring, operational efficiency, resource optimization, and precision farming practices [39]. However, despite the growing interest in digital agriculture and smart farming technologies, several important research gaps remain insufficiently addressed within the existing literature.

First, limited studies have comprehensively integrated multi-source agricultural information systems with regional agricultural adaptation strategies. Existing smart agriculture research has primarily concentrated on technological innovation, system architecture, data processing efficiency, and sensor integration capabilities rather than examining how integrated agricultural platforms contribute to regional agricultural resilience and adaptive farming systems under varying climatic and environmental conditions [35]. Regional agricultural adaptation has become increasingly important due to climate change, environmental variability, water scarcity, and regional productivity instability, yet the role of integrated information fusion platforms in supporting adaptive agricultural management remains underexplored.

Second, most previous studies have focused predominantly on the technical performance of smart agricultural technologies, such as detection accuracy, algorithm optimization, data transmission speed, and computational efficiency, while giving relatively less attention to broader agricultural sustainability outcomes [26]. Although technological advancements are essential for smart farming implementation, sustainable agriculture requires a broader understanding of how digital agricultural systems contribute to long-term productivity, resource-use efficiency, environmental sustainability, and regional farming resilience. Consequently, the absence of sustainability-oriented discussions within smart agricultural integration research limits the practical and strategic applicability of these technologies in achieving sustainable agricultural transformation.

Furthermore, there remains a lack of comprehensive theoretical and conceptual frameworks linking multi-source information fusion platforms, agricultural efficiency, and regional adaptation outcomes. Existing literature often investigates these variables independently, without sufficiently explaining the interrelationships among integrated agricultural technologies, operational efficiency, and adaptive farming capabilities. This fragmented approach creates limitations in understanding the mechanisms through which smart agricultural integration platforms influence agricultural performance and regional sustainability simultaneously. In addition, limited theoretical integration exists between smart agricultural technologies and regional farming resilience perspectives. While theories such as the Diffusion of Innovation (DOI) Theory and Technology Acceptance Model (TAM) have frequently been applied to technology adoption studies, their integration within sustainable regional agricultural adaptation contexts remains insufficiently explored [14].

Another important gap concerns the limited number of studies examining the role of integrated agricultural data systems in supporting sustainable agricultural transformation at regional levels. Many studies focus on isolated precision agriculture applications rather than investigating comprehensive digital agricultural ecosystems capable of supporting coordinated agricultural management, environmental monitoring, and adaptive regional farming strategies. The increasing complexity of modern agricultural systems requires integrated data-driven platforms capable of supporting real-time decision-making, climate adaptation, and sustainable agricultural development simultaneously.

Although DOI and TAM have been extensively employed to explain agricultural technology adoption, their application has predominantly focused on adoption intention or technology acceptance as the final outcome. Less attention has been given to explaining how the adoption and effective utilisation of integrated agricultural technologies subsequently translate into operational and regional sustainability outcomes. This represents an important theoretical gap because adoption alone does not necessarily generate agricultural value; the technology must be effectively utilised to improve agricultural operations. Accordingly, the present study integrates DOI and TAM as complementary theoretical perspectives and extends the adoption logic beyond technology acceptance by linking smart agricultural platform utilisation with agricultural efficiency and, subsequently, regional agricultural adaptation. This approach shifts the theoretical emphasis from explaining merely whether agricultural stakeholders adopt technology toward understanding how accepted and effectively utilised digital agricultural innovations may generate operational efficiency and adaptive agricultural outcomes.

2. Methodology

2.1 Research Design

This study adopts a quantitative research approach to examine the role of multi-source information fusion smart agricultural integration platforms in enhancing agricultural efficiency and regional adaptation. Quantitative research is widely applied in smart agriculture and technology adoption studies because it enables researchers to systematically measure relationships among variables using statistical analysis and empirical evidence. The quantitative approach provides a structured method for examining the relationships between technological integration, operational efficiency, and sustainable agricultural outcomes through numerical data collection and hypothesis testing. Recent studies in smart agriculture emphasized that quantitative methods are highly effective for evaluating technology-driven agricultural systems, particularly in studies involving artificial intelligence (AI), Internet of Things (IoT), data analytics, and precision farming technologies. Moreover, quantitative approaches allow researchers to assess causal relationships, validate conceptual frameworks, and generate generalizable findings related to agricultural digitalization and smart farming adoption.

The study further employs a cross-sectional research design, where data are collected from respondents at a single point in time to examine perceptions, adoption patterns, and operational outcomes associated with smart agricultural integration platforms. Cross-sectional designs are commonly used in agricultural technology and sustainability research because they provide efficient and practical approaches for investigating relationships between variables within a specific population or geographical context. Previous smart agriculture studies have utilized cross-sectional survey methods to examine technology acceptance, agricultural efficiency, climate-smart agriculture adoption, and sustainable farming practices among farming communities and agricultural stakeholders. The use of a cross-sectional design in this study is appropriate because it enables the researcher to analyze the current state of smart agricultural platform adoption and its influence on agricultural efficiency and regional adaptation without requiring long-term observation periods.

In addition, this study develops a conceptual model to explain the relationships between multi-source information fusion smart agricultural integration platforms, agricultural efficiency, and regional agricultural adaptation. The proposed conceptual model integrates perspectives from the Diffusion of Innovation (DOI) Theory, Technology Acceptance Model (TAM), and smart agriculture sustainability literature to provide a comprehensive understanding of digital agricultural transformation. Conceptual model development is important in smart agriculture research because agricultural systems involve multiple interconnected technological, environmental, and operational dimensions. Recent studies highlighted the importance of integrated digital agricultural frameworks and multi-source information systems in improving agricultural decision-making, interoperability, sustainability, and adaptive farming strategies. The conceptual framework proposed in this study therefore provides a theoretical foundation for understanding how integrated agricultural information platforms contribute toward operational efficiency and sustainable regional agricultural adaptation in smart farming environments.

2.2 Model Development

The conceptual model proposed in this study explains the relationship between multi-source information fusion smart agricultural integration platforms, agricultural efficiency, and regional agricultural adaptation within the context of smart and sustainable agriculture. The model is grounded in the assumption that integrating heterogeneous agricultural data sources through intelligent digital platforms can significantly improve agricultural operational performance and adaptive farming capacity. The framework further proposes that agricultural efficiency functions as a mediating mechanism linking smart agricultural integration platforms and regional adaptation outcomes.

The first relationship in the conceptual model focuses on the influence of multi-source information fusion smart agricultural integration platforms on agricultural efficiency. Multi-source information fusion refers to the integration of heterogeneous agricultural data obtained from various sources, including Internet of Things (IoT) sensors, climate monitoring systems, satellite imagery, soil data, crop imaging systems, and farm management technologies. Recent studies emphasized that integrated data fusion technologies improve precision farming accuracy, predictive analytics, and intelligent agricultural decision-making processes. Through real-time monitoring and AI-driven analytics, smart agricultural integration platforms enable more precise resource allocation, efficient irrigation management, crop monitoring, disease detection, and operational optimization. Studies have shown that multi-source information fusion systems significantly enhance agricultural productivity and operational efficiency compared to traditional single-source agricultural systems [43]. Therefore, the study proposes that the integration capability of smart agricultural platforms positively contributes to agricultural efficiency through improved data-driven farming management and resource optimization.

The second relationship in the conceptual framework examines the effect of agricultural efficiency on regional agricultural adaptation. Agricultural efficiency refers to the ability of farming systems to optimize inputs, improve productivity, reduce operational waste, and enhance sustainable agricultural performance. In the context of climate variability and regional agricultural challenges, operational efficiency becomes an essential factor supporting adaptive agricultural resilience. Previous studies highlighted that smart agriculture technologies improve climate-responsive farming systems by supporting efficient water management, crop health monitoring, predictive decision-making, and sustainable resource utilization [2] Efficient agricultural systems enable farming communities to better respond to regional environmental conditions, climate uncertainties, and productivity fluctuations. Furthermore, climate-smart agricultural frameworks emphasize that operational efficiency contributes significantly toward agricultural sustainability, resilience, and long-term adaptive capacity across diverse farming environments. Consequently, this study proposes that higher agricultural efficiency positively influences regional agricultural adaptation through enhanced resilience, sustainability, and adaptive farming performance.

In addition, the conceptual model proposes that agricultural efficiency mediates the relationship between multi-source information fusion smart agricultural integration platforms and regional agricultural adaptation. Smart agricultural integration platforms alone may not directly improve regional adaptation unless the information generated by these systems effectively enhances agricultural operational performance. The mediation mechanism suggests that integrated data systems improve adaptive agricultural outcomes primarily through their ability to optimize farming efficiency, productivity, and resource management. Recent studies demonstrated that machine learning-based information fusion systems improve intelligent agricultural decision-making and adaptive agricultural management by integrating climatic, biological, soil, and imaging data into unified operational platforms [7]. Moreover, AI-driven agricultural systems facilitate more accurate predictions, adaptive resource allocation, and region-specific agricultural strategies that strengthen farming resilience under changing environmental conditions. Therefore, agricultural efficiency serves as a critical mechanism translating technological integration into sustainable regional agricultural adaptation outcomes.

Overall, the conceptual model highlights the strategic importance of multi-source information fusion technologies in advancing smart agriculture, agricultural sustainability, and adaptive farming systems. The framework contributes to the growing literature on digital agriculture by integrating information fusion systems, operational efficiency, and regional adaptation perspectives within a unified smart agriculture model.

2.3 Hypothesis Development

Multi-source information fusion smart agricultural integration platforms have become increasingly important in improving agricultural efficiency through the integration of heterogeneous agricultural datasets such as soil information, climate data, satellite imagery, sensor networks, unmanned aerial vehicle (UAV) monitoring, and farm management systems. The integration of multiple data sources allows farmers and agricultural stakeholders to make more accurate, timely, and data-driven decisions regarding irrigation, fertilization, crop monitoring, disease detection, and resource allocation. Previous studies emphasized that information fusion technologies significantly improve predictive accuracy, operational optimization, and intelligent agricultural decision-making within smart farming environments [5]. In addition, machine learning-based multimodal data fusion systems were found to improve crop monitoring, yield estimation, soil moisture analysis, and environmental management by effectively combining various agricultural data sources [7,43].

Furthermore, smart agricultural integration platforms support precision agriculture by improving operational efficiency, reducing resource wastage, and optimizing agricultural productivity through real-time monitoring and intelligent analytics. Information fusion systems enable farmers to respond more effectively to changing environmental conditions and farming requirements while enhancing sustainable agricultural practices. Recent studies suggested that the integration of AI, IoT, remote sensing, and data fusion technologies substantially improves agricultural monitoring and farm management efficiency [30].

H1: Multi-Source Information Fusion Smart Agricultural Integration Platforms and Agricultural Efficiency

Agricultural efficiency plays a crucial role in enhancing regional agricultural adaptation, particularly under conditions of climate variability, environmental uncertainty, and resource scarcity. Efficient agricultural systems improve farmers' ability to optimize resource utilization, maintain productivity stability, and adapt to region-specific environmental conditions. Precision agriculture technologies and smart farming systems contribute to adaptive agricultural management by enabling more accurate monitoring of crops, climate, soil conditions, and environmental stress factors. Previous studies reported that agricultural efficiency supported by smart technologies improves climate resilience, productivity sustainability, and adaptive farming strategies across different agricultural regions (5,21].

Moreover, efficient agricultural systems reduce operational inefficiencies and strengthen the capacity of agricultural communities to respond to regional environmental challenges through data-driven and climate-responsive farming strategies. Smart agricultural systems facilitate adaptive decision-making processes that support sustainable production under varying climatic and geographical conditions. Research on AI-enabled smart agriculture further demonstrated that intelligent farming technologies improve environmental adaptability, crop resilience, and sustainable agricultural transformation [4,30].

H2: Agricultural Efficiency and Regional Agricultural Adaptation

Agricultural efficiency is proposed to mediate the relationship between multi-source information fusion smart agricultural integration platforms and regional agricultural adaptation. Smart agricultural integration platforms generate value not only through technological innovation but also through their ability to improve operational efficiency, optimize resource utilization, and enhance precision agricultural management. The integration of multi-source data fusion systems enables more effective agricultural monitoring, predictive analytics, and intelligent decision-support mechanisms that subsequently contribute to efficient agricultural operations and adaptive farming systems [47].

In addition, agricultural efficiency serves as an important operational mechanism that translates technological capabilities into sustainable agricultural outcomes. Efficient agricultural management strengthens the adaptability of farming systems to regional climate conditions, environmental variability, and resource limitations. Previous studies emphasized that smart farming technologies and multimodal agricultural systems improve sustainability and adaptive agricultural performance through enhanced operational optimization and intelligent farm management [5,7].

H3: Mediating Role of Agricultural Efficiency

2.6 Conceptual Framework

The conceptual framework of this study proposes that multi-source information fusion smart agricultural integration platforms play a significant role in enhancing agricultural efficiency, which subsequently contributes to regional agricultural adaptation and sustainability. The framework positions the multi-source information fusion smart agricultural integration platform as the independent variable, agricultural efficiency as the mediating variable, and regional agricultural adaptation as the dependent variable. The independent variable encompasses several important dimensions, including data integration capability, real-time monitoring systems, AI-driven analytics, IoT connectivity, and decision-support functionality. These technological capabilities enable the integration and analysis of diverse agricultural information sources, allowing farmers and agricultural stakeholders to improve precision farming practices, optimize resource allocation, and strengthen agricultural decision-making processes.

The framework further proposes that agricultural efficiency serves as a critical mechanism linking smart agricultural integration platforms and regional agricultural adaptation. Agricultural efficiency is reflected through resource optimization, operational efficiency, productivity enhancement, cost reduction, and precision farming efficiency. Through intelligent data integration and real-time agricultural monitoring, smart agricultural platforms are expected to improve operational performance and sustainable farming practices. Improved agricultural efficiency subsequently supports regional agricultural adaptation by enhancing climate adaptability, sustainable farming resilience, regional productivity stability, environmental adaptability, and overall agricultural sustainability performance. Therefore, the framework suggests that the implementation of multi-source information fusion technologies not only improves farming efficiency but also strengthens the adaptability and resilience of agricultural systems under varying environmental and regional conditions. The proposed framework provides a theoretical foundation for understanding the relationship between digital agricultural technologies, operational efficiency, and sustainable regional agricultural development.

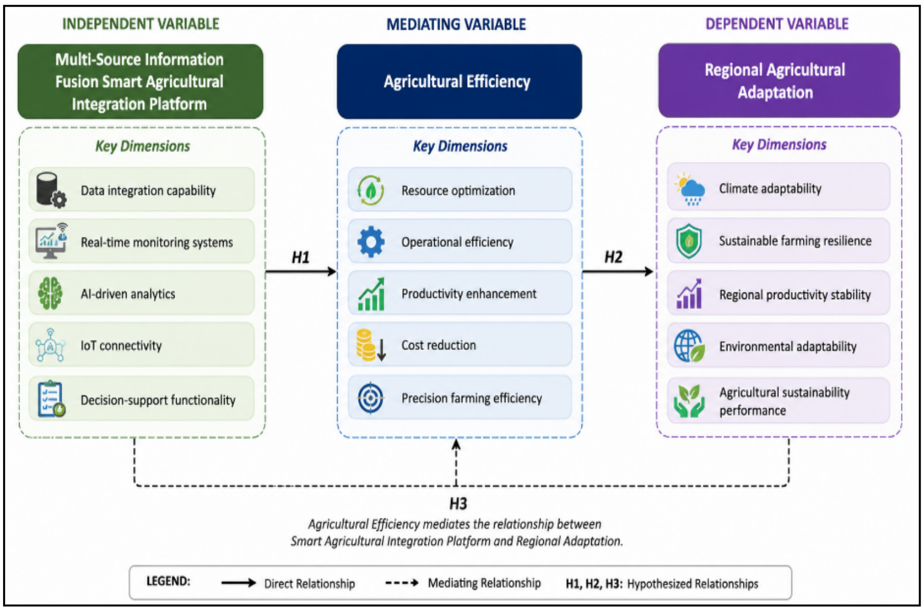

Fig. 2. Conceptual framework

3. Discussion

3.1 Smart Agricultural Integration Platforms and Agricultural Efficiency

Smart agricultural integration platforms have emerged as important technological solutions for improving agricultural efficiency, sustainability, and operational effectiveness in modern farming systems. The integration of artificial intelligence (AI), Internet of Things (IoT), big data analytics, remote sensing, and multi-source agricultural information systems enables farmers and agricultural stakeholders to monitor, manage, and optimize farming operations in real time. These platforms support data-driven agricultural management by integrating multiple streams of agricultural information, including soil conditions, weather patterns, crop health, irrigation status, and farm operational data into unified decision-support systems. Recent studies highlighted that smart farming technologies significantly improve agricultural productivity, resource optimization, and environmental sustainability through advanced digital integration and intelligent automation [40].

One of the major contributions of smart agricultural integration platforms is their capability to provide real-time agricultural monitoring. Real-time monitoring systems utilize sensors, drones, satellite imagery, and IoT-enabled devices to continuously collect and analyze agricultural data across farming environments. These technologies enable farmers to detect crop stress, soil nutrient deficiencies, pest infestations, irrigation needs, and climate-related risks more efficiently and accurately. According to Sharma and Shivandu [40], AI-integrated IoT systems improve crop monitoring and management through real-time sensing, remote monitoring, and automated agricultural analytics, thereby enhancing farming precision and reducing operational uncertainty. Similarly, Qwaid et al. (2026) emphasized that AI-driven smart farming frameworks enable predictive diagnostics, automated environmental control, and real-time agricultural management, particularly in climate-sensitive agricultural regions. These capabilities improve farm responsiveness and contribute toward more adaptive and resilient agricultural systems.

AI-enabled agricultural technologies may also contribute to more efficient chemical input management when they are integrated with precision application systems. The mechanism is primarily based on improved targeting rather than an inherent chemical-reduction effect of AI itself. Machine vision and deep-learning models can identify weeds, crop conditions, or treatment areas, while variable-rate or site-specific application technologies translate this information into targeted interventions. Empirical evidence demonstrates the potential of this approach. Deep-learning-based variable spraying has achieved pesticide savings relative to constant spraying, while CNN-based precision sprayers have demonstrated substantial reductions in spray volume under field conditions. Recent machine-vision-based orchard experiments similarly reported considerable reductions in spray volume compared with continuous spraying. Nevertheless, these benefits should not be generalized across all AI applications or agricultural environments because actual reductions depend on detection accuracy, crop characteristics, weed or pest distribution, application equipment, operating conditions, and the baseline spraying method used for comparison.

Another important contribution of smart agricultural integration platforms is precision resource allocation. Precision agriculture technologies allow farmers to optimize the use of agricultural inputs such as water, fertilizers, pesticides, and energy based on real-time field conditions and crop requirements. By integrating multi-source agricultural information, smart platforms can support variable-rate application technologies, precision irrigation systems, and targeted crop management strategies that reduce waste and improve operational efficiency. Kumari et al. (2025) found that AI-enabled precision farming systems improve sustainability and efficiency by optimizing resource utilization through intelligent monitoring and predictive analysis. Similarly, Singh and Singh (2024) highlighted that smart farming technologies supported by IoT and AI significantly improve precision resource allocation, crop productivity, and environmental sustainability while minimizing operational inefficiencies and agricultural waste. Consequently, smart agricultural platforms contribute toward sustainable agricultural intensification and more efficient farming practices.

Moreover, data-driven agricultural decision-making represents one of the most transformative features of smart agricultural integration systems. Multi-source information fusion platforms enable the integration and analysis of large-scale agricultural datasets generated from sensors, drones, satellite imagery, farm equipment, and environmental monitoring systems. These integrated systems support evidence-based farming decisions that improve productivity, profitability, and climate adaptability. Recent studies highlighted that data-driven agricultural management improves operational optimization, predictive risk management, and precision farm planning through advanced analytics and machine learning technologies [44]. Additionally, AI-powered agricultural systems are increasingly recognized as important tools for supporting climate-smart agriculture, improving agricultural resilience, and enhancing food security under changing environmental conditions.

Finally, smart farming operational optimization is achieved through the integration of intelligent automation, predictive analytics, and coordinated agricultural management systems. Smart agricultural integration platforms improve farm operational efficiency by reducing manual dependency, increasing process automation, optimizing labor utilization, and enhancing coordination across agricultural activities. AI-supported operational systems can automate irrigation scheduling, nutrient management, disease detection, and field monitoring processes, enabling more efficient and sustainable farm management practices. Recent studies suggested that smart agricultural platforms integrating AI, IoT, cloud computing, and edge analytics significantly enhance agricultural operational performance and adaptive farming capabilities [11,37]. Therefore, smart agricultural integration platforms represent an important advancement toward efficient, data-driven, and sustainable agricultural transformation.

3.2 Agricultural Efficiency and Regional Adaptation

Agricultural efficiency plays a critical role in supporting regional adaptation and sustainable farming systems under increasing climate variability and environmental uncertainty. Modern agricultural systems are increasingly required to balance productivity growth with environmental sustainability and climate resilience. Climate-responsive farming systems have emerged as essential strategies for improving adaptive agricultural capacity by integrating precision farming technologies, climate-smart agriculture (CSA), and digital agricultural management practices. Recent studies emphasized that climate-smart agricultural systems enhance agricultural productivity, improve climate resilience, and reduce environmental risks through adaptive farming strategies and efficient resource management [10,24]. Furthermore, climate-responsive farming approaches enable farmers to respond more effectively to changing environmental conditions, including droughts, temperature fluctuations, flooding, and soil degradation, thereby strengthening long-term agricultural sustainability [18,44].

In addition, sustainable agricultural resilience has become increasingly important in maintaining food security and farming continuity across different geographical regions. Agricultural resilience refers to the ability of farming systems to withstand, adapt to, and recover from environmental, economic, and climatic disruptions while maintaining productivity and operational stability. Recent evidence suggests that smart farming systems, digital agriculture, and precision resource management significantly contribute to agricultural resilience by optimizing water use, fertilizer application, energy efficiency, and crop management practices [22]. Smart agricultural technologies also support adaptive decision-making processes by integrating satellite data, climate information, sensor networks, and AI-driven analytics into agricultural management systems, thereby enhancing regional farming resilience and sustainability.

Moreover, productivity stability across regions has become a major concern due to uneven climate impacts and regional environmental differences affecting agricultural performance. Climate change has significantly influenced agricultural productivity worldwide, with stronger negative impacts observed in vulnerable and warmer regions. Previous studies reported that climate change has reduced global agricultural productivity growth and increased regional disparities in agricultural performance [32]. Consequently, improving agricultural efficiency through data-driven and adaptive farming technologies may help stabilize agricultural productivity across regions by enabling better resource allocation, climate forecasting, and region-specific farming strategies. Multi-source information fusion systems are particularly valuable because they facilitate the integration of real-time environmental, climatic, and operational data for more accurate agricultural decision-making and regional adaptation planning.

Environmental sustainability also represents a central component of agricultural efficiency and regional adaptation. Conventional farming systems are often associated with excessive resource consumption, soil degradation, greenhouse gas emissions, and biodiversity loss. In contrast, sustainable agricultural practices supported by smart farming technologies promote efficient land use, reduced chemical dependency, optimized water management, and lower environmental impacts [42,44]. Climate-smart agriculture further supports environmental sustainability by integrating adaptive and mitigation strategies that improve ecosystem resilience while maintaining agricultural productivity [24]. These sustainable agricultural approaches are increasingly important for supporting long-term regional agricultural adaptation and ecological balance.

Finally, agricultural efficiency contributes significantly toward enhancing regional agricultural competitiveness in the global agricultural economy. Regions capable of adopting advanced agricultural technologies, smart farming systems, and climate-responsive management practices are more likely to maintain stable agricultural outputs, improve product quality, reduce operational costs, and strengthen food security. Smart agricultural integration platforms facilitate efficient coordination between technological innovation, agricultural management, and regional adaptation strategies, thereby increasing the competitiveness and resilience of agricultural regions. As agricultural markets become increasingly influenced by climate uncertainty and sustainability standards, regions adopting efficient and adaptive agricultural systems may gain substantial economic and strategic advantages in agricultural production and food supply management.

3.3 Mediating Role of Agricultural Efficiency

Agricultural efficiency plays a crucial mediating role in linking multi-source information fusion smart agricultural integration platforms with regional agricultural adaptation and sustainability outcomes. The integration of advanced smart agricultural technologies, including artificial intelligence (AI), Internet of Things (IoT), remote sensing, satellite systems, and multi-source data fusion, enables farmers and agricultural managers to optimize farming operations, improve resource allocation, and enhance overall agricultural productivity. Operational efficiency contributes significantly to adaptive agricultural systems because efficient farming practices allow agricultural sectors to respond more effectively to climate variability, environmental uncertainties, and region-specific agricultural challenges. Recent studies emphasized that smart agriculture technologies improve operational efficiency by supporting real-time monitoring, precision resource management, predictive analytics, and intelligent decision-making processes in farming systems [40].

The mediating role of agricultural efficiency can be explained through the ability of smart agricultural integration platforms to transform fragmented agricultural data into actionable insights that improve operational performance. Multi-source information fusion systems integrate heterogeneous agricultural data sources such as soil conditions, climate information, satellite imagery, crop health indicators, irrigation systems, and farm management databases to provide comprehensive agricultural intelligence. These integrated systems improve farming precision, reduce unnecessary resource usage, optimize fertilizer and water application, and enhance productivity stability across different agricultural regions. Previous research demonstrated that information fusion technologies and machine learning-based smart farming systems significantly enhance predictive accuracy, crop monitoring efficiency, and agricultural management performance [5].

Consequently, agricultural efficiency becomes the operational mechanism through which smart technologies contribute to regional agricultural resilience and sustainability.

Furthermore, operational efficiency contributes directly toward adaptive agricultural systems by improving the flexibility and responsiveness of agricultural practices under changing environmental conditions. Smart farming systems equipped with AI-driven analytics and real-time monitoring capabilities enable region-specific agricultural strategies that support climate adaptation and sustainable farming management. Efficient agricultural operations reduce production costs, minimize environmental degradation, and improve long-term agricultural resilience. Studies found that precision agriculture and IoT-enabled farming systems contribute significantly toward sustainable crop production, environmental conservation, and regional agricultural competitiveness through optimized resource utilization and intelligent farm management [41]. In addition, AI and remote sensing technologies have been shown to strengthen climate-smart agricultural systems by enhancing land-use efficiency, improving crop monitoring, and supporting adaptive farming decisions across diverse agricultural environments [13,30].

The mechanisms linking smart technologies and regional sustainability are also closely associated with the ability of agricultural integration platforms to support sustainable intensification and resource optimization. Through intelligent data fusion and automated decision-support systems, smart agricultural platforms facilitate more precise and environmentally responsible agricultural practices. These systems enable early detection of environmental stress, accurate irrigation scheduling, optimized nutrient management, and efficient pest and disease monitoring, which collectively contribute to sustainable agricultural transformation. Recent studies highlighted that multimodal data fusion technologies improve intelligent agricultural decision-making and strengthen sustainability-oriented agricultural management systems [7]. Therefore, agricultural efficiency serves not only as an operational outcome but also as a strategic mechanism connecting digital agricultural technologies with regional adaptation capacity and long-term agricultural sustainability.

Overall, the mediating role of agricultural efficiency demonstrates that the effectiveness of multi-source information fusion smart agricultural integration platforms extends beyond technological performance alone. Instead, the operational improvements generated through enhanced efficiency act as the key pathway through which smart agricultural technologies contribute to adaptive, resilient, and sustainable agricultural systems across different regional contexts.

3.4 Theoretical Implications

The principal theoretical contribution of this study lies in integrating the Diffusion of Innovation (DOI) Theory and Technology Acceptance Model (TAM) within a broader outcome-oriented framework for smart agriculture. Rather than applying DOI and TAM as parallel explanations of technology adoption, the proposed framework treats them as complementary theoretical perspectives operating at different but interconnected stages of agricultural digitalisation. DOI explains how characteristics of multi-source information fusion platforms, including relative advantage, compatibility, complexity, trialability, and observability, influence their diffusion and adoption within agricultural environments. TAM complements this perspective by explaining how users evaluate these technologies in terms of perceived usefulness and perceived ease of use. The integration therefore connects innovation-level characteristics with user-level technological evaluations.

More importantly, the study extends this integrated adoption perspective beyond behavioural intention or initial acceptance. The proposed framework argues that the theoretical significance of smart agricultural technology adoption ultimately depends on whether accepted technologies are effectively utilised to generate operational improvements. Agricultural efficiency is therefore positioned as the mechanism through which the technological capabilities of multi-source information fusion platforms are translated into broader regional adaptation outcomes. This creates a theoretical progression from innovation characteristics (DOI), to technology evaluation and acceptance (TAM), to effective platform utilisation, agricultural efficiency, and regional agricultural adaptation. The framework consequently contributes to the smart-agriculture literature by connecting technology-adoption theories with operational and adaptation outcomes rather than treating adoption as the terminal outcome of digital agricultural transformation.

3.5 Practical Implications

The findings of this study provide several important practical implications for the development of smart agriculture policies and sustainable agricultural transformation. Governments and agricultural authorities should strengthen policy frameworks that support the adoption of multi-source information fusion platforms, artificial intelligence (AI), Internet of Things (IoT) technologies, and digital agricultural ecosystems. Smart agriculture policies should focus on improving digital infrastructure, expanding rural internet connectivity, supporting agricultural data-sharing systems, and encouraging investment in AI-driven agricultural innovation. Recent studies emphasized that policy support, infrastructure development, and institutional collaboration are essential for accelerating smart farming adoption and achieving sustainable agricultural modernization [45]. In addition, governments should provide financial incentives, subsidies, and technical assistance programs to reduce barriers to technology adoption among farmers, particularly in rural and climate-vulnerable regions.

The study also highlights the importance of agricultural digitalization strategies in enhancing agricultural efficiency and regional adaptation. Agricultural digitalization involves integrating big data analytics, remote sensing, cloud computing, satellite technologies, and intelligent farm management systems into agricultural operations. Multi-source information fusion platforms enable the collection and integration of real-time agricultural data from diverse sources, allowing more accurate monitoring of crops, soil conditions, climate variability, and resource utilization. Previous research demonstrated that digital agriculture technologies improve decision-making processes, optimize resource allocation, and increase operational efficiency in precision farming systems. Consequently, agricultural institutions and policymakers should prioritize digital transformation strategies that support data interoperability, integrated agricultural databases, and smart agricultural management platforms to improve productivity and sustainability.

Furthermore, the implementation of AI and IoT technologies in agriculture represents a critical advancement toward intelligent and adaptive farming systems. AI-driven analytics combined with IoT-enabled sensors allow farmers to monitor environmental conditions, crop health, irrigation systems, soil nutrients, and pest infestations in real time. These technologies support predictive decision-making, precision resource management, and automated agricultural operations that significantly reduce waste and operational costs. Recent studies indicated that AI and IoT integration enhances precision agriculture by enabling site-specific farming interventions, improving productivity, and strengthening agricultural resilience against climate change and environmental uncertainty. In addition, AI-powered smart farming systems contribute to sustainable agricultural intensification by improving resource-use efficiency while minimizing environmental impacts.

The study also provides practical implications for sustainable regional agricultural planning. Multi-source information fusion platforms can assist governments, agricultural agencies, and regional planners in developing adaptive agricultural strategies tailored to specific environmental, climatic, and socio-economic conditions. Smart agricultural systems enable more accurate forecasting, climate-risk assessment, and resource planning that support long-term agricultural sustainability and regional resilience. Recent research highlighted that information and communication technologies (ICT), AI systems, and smart agricultural platforms play a significant role in sustainable rural planning, climate-responsive farming systems, and regional agricultural development [6,48]. Through integrated agricultural intelligence systems, policymakers and planners can design region-specific agricultural policies that improve food security, environmental sustainability, and farming resilience in response to climate variability and changing agricultural demands.

Overall, the practical implications of this study suggest that the integration of multi-source information fusion technologies, AI, IoT systems, and digital agricultural platforms may significantly contribute toward the modernization of agriculture, sustainable resource management, and regional agricultural adaptation. The findings offer valuable insights for policymakers, researchers, agricultural technologists, and farming communities seeking to promote intelligent, sustainable, and resilient agricultural systems.

3.6 Future Research Directions

Future research should empirically validate the proposed framework by testing the relationship between multi-source information fusion smart agricultural integration platforms, agricultural efficiency, and regional agricultural adaptation. Although recent studies show that AI, IoT, big data, and multi-source sensing technologies can improve monitoring, resource optimization, and predictive decision-making in agriculture, further quantitative studies are needed to confirm how these technologies influence actual farm-level efficiency and adaptation outcomes across different farming systems [2].

Future studies should also conduct comparative regional agricultural research to examine whether the effectiveness of smart agricultural integration platforms differs according to climate conditions, soil characteristics, crop types, infrastructure readiness, and farmers' digital literacy. This is important because regional adaptation depends not only on technology availability but also on local environmental conditions and farmers' willingness to adopt digital farming practices [5].

In addition, future research should further investigate the integration of AI, satellite systems, remote sensing, IoT sensors, and predictive analytics within smart agricultural platforms. Recent studies emphasize that combining satellite data, sensor-based monitoring, climate analytics, and machine learning can strengthen crop monitoring, yield prediction, pest detection, irrigation planning, and resource allocation. Therefore, future models should move beyond single-source agricultural data and examine how multi-source information fusion improves the accuracy and usefulness of agricultural decision-support systems.

Finally, longitudinal studies are recommended to examine how smart agricultural platforms influence agricultural efficiency and regional adaptation over time. Cross-sectional studies may explain short-term perceptions and adoption intention, but longitudinal research can capture long-term changes in productivity, cost efficiency, climate resilience, and sustainable farming performance. Bocean (2024) emphasized the importance of longitudinal analysis in understanding the relationship between agricultural digitalization and sustainability outcomes. Therefore, future studies should track farms, regions, or agricultural cooperatives across multiple production seasons to provide stronger evidence on the long-term benefits of smart agricultural integration platforms.

4. Conclusions

This study develops a conceptual framework explaining how multi-source information fusion smart agricultural integration platforms may contribute to agricultural efficiency and regional agricultural adaptation. The framework proposes that the value of integrated digital agricultural technologies lies not merely in combining heterogeneous data sources, but in their capacity to translate integrated information into more effective agricultural decision-making and resource management. Agricultural efficiency is therefore positioned as a key mediating mechanism through which smart agricultural integration platforms may contribute to broader regional adaptation outcomes.

The study also contributes theoretically by drawing on the complementary perspectives of the Diffusion of Innovation (DOI) Theory and Technology Acceptance Model (TAM). DOI explains the innovation characteristics that may encourage the adoption of smart agricultural platforms, whereas TAM explains users' evaluations of their usefulness and ease of use. By connecting these perspectives with agricultural efficiency and regional adaptation, the proposed framework extends the discussion beyond technology adoption toward understanding how the effective utilisation of digital agricultural systems may generate operational and adaptive value.

As a conceptual study, however, the proposed relationships require empirical validation. Future research should test the framework across different agricultural regions, farming systems, crop types, climatic conditions, and levels of digital readiness. Longitudinal and comparative studies would be particularly valuable for determining whether improvements in agricultural efficiency generated through smart agricultural platforms translate into sustained regional adaptation over time. Overall, the study provides a theoretical basis for future research examining how integrated digital agricultural systems can support more efficient, adaptive, and sustainable agricultural development.

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. 2025. “Adoption of Innovative Technologies for Sustainable Agriculture: A Scoping Review of the System Domain.” *Sustainability* 17 (9): 4224. https://doi.org/10.3390/su17094224.

[2] Ahmed, Bilal, Hasnat Shabbir, Syed Rameez Naqvi, and Lu Peng. 2024. “Smart Agriculture: Current State, Opportunities and Challenges.” *IEEE Access*. https://doi.org/10.1109/ACCESS.2024.0429000.

[3] Ali, Mohammed Umar. 2025. “Smart Agriculture: Integration of IoT, AI and Big Data in Farm Management.” *Journal of Scientific Research and Reports* 31 (12): 114–122. https://doi.org/10.9734/jsrr/2025/v31i123756.

[4] Alreshidi, Eissa. 2019. “Smart Sustainable Agriculture (SSA) Solution Underpinned by Internet of Things (IoT) and Artificial Intelligence (AI).” *arXiv*. https://doi.org/10.48550/arXiv.1906.03106.

[5] Allu, Ayyappa Reddy, and Shashi Mesapam. 2025. “Impact of Remote Sensing Data Fusion on Agriculture Applications: A Review.” *European Journal of Agronomy* 164: 127478. https://doi.org/10.1016/j.eja.2024.127478.

[6] Ashir, Dewan Md Nur Anjum, Md. Taimur Ahad, Manosh Talukder, and Tahsinur Rahman. 2022. Internet of Things (IoT) Based Smart Agriculture Aiming to Achieve Sustainable Goals.” *arXiv*. https://doi.org/10.48550/arXiv.2206.06300.

[7] Basnayake, R. N. I. 2026. “Multimodal Data Fusion in Smart Agriculture: Integrating Soil, Climate, Imaging, and Biological Signals Using Machine Learning: Scoping Review.” *International Journal of Research and Innovation in Applied Science* 11 (15): 101–107. https://doi.org/10.51584/IJRIAS.2026.111500010.

[8] Babar, Adil Z., and Ozgur B. Akan. 2024. “Sustainable and Precision Agriculture with the Internet of Everything (IoE).” *arXiv*. https://doi.org/10.48550/arXiv.2404.06341.

[9] Basnayake, R. N. I. 2026. “Multimodal Data Fusion in Smart Agriculture: Integrating Soil, Climate, Imaging, and Biological Signals Using Machine Learning: Scoping Review.” *International Journal of Research and Innovation in Applied Science* 11 (15): 101–107. https://doi.org/10.51584/IJRIAS.2026.111500010.

[10] Begna, T. 2025. “Climate-Smart Agriculture: Effect of Climate Change on Sustainable Farming Systems.” *International Journal of Agronomy*. https://doi.org/10.1155/ioa/9972955.

[11] Bompotas, Agorakis, Konstantinos Koutras, Nikitas Rigas Kalogeropoulos, Panagiotis Kechagias, Dimitra Gariza, Athanasios P. Kalogeras, and Christos Alexakos. 2025. “SUSTAINABLE Platform: Seamless Smart Farming Integration Towards Agronomy Automation.” *arXiv*. https://doi.org/10.48550/arXiv.2510.26989

[12] Chen, X. 2022. “Diffusion of Agricultural Technology Innovation: Research Trends and Future Directions.” *Sustainability* 14 (22): 15008. https://doi.org/10.3390/su142215008.

[13] Chen, X. 2025. “The Role of Modern Agricultural Technologies in Improving Agricultural Productivity and Land Use Efficiency.” *Frontiers in Plant Science* 16. https://doi.org/10.3389/fpls.2025.1675657.

[14] Davis, Fred D. 1989. “Perceived Usefulness, Perceived Ease of Use, and User Acceptance of Information Technology.” *MIS Quarterly* 13 (3): 319–340. https://doi.org/10.2307/249008.

[15] Dhanasekar, S., et al. 2025. “A Comprehensive Review on Current Issues and Potential Directions of IoT-Based Smart Farming.” *Computer Communications*. https://doi.org/10.1016/j.comcom.2024.107777.

[16] de Avila, Felipe Rodrigues, Carlos Eduardo Angeli Furlani, Mariana Barbosa de Souza, Gabriel Henrique de Oliveira, Lucas Eduardo de Lima Melquiades, and João Pedro de Souza. 2025. “Smart Environments in Digital Agriculture: A Systematic Review.” *Computers and Electronics in Agriculture*. https://doi.org/10.1016/j.compag.2025.110499.

[17] Delfani, Parham, Alireza Khosravi, Saeid Nahavandi, and Darius Nahavandi. 2024. “IoT, ML and AI for Disease Forecasting Amidst Climate Change.” *Precision Agriculture*. https://doi.org/10.1007/s11119-024-10164-7.

[18] Devarajan, Y. 2026. “Adapting Agriculture for Climate Resilience: Strategies and Challenges.” *Climate Resilience and Sustainability*. https://doi.org/10.1016/j.crsust.2026.100672.

[19] Duguma, A. L., et al. 2024. “How the Internet of Things Technology Improves Agricultural Sustainability and Efficiency.” *Artificial Intelligence Review*. https://doi.org/10.1007/s10462-024-11046-0.

[20] Gashure, Sibilo, et al. 2025. “Impacts of Climate Variability and Adaptation Strategies on Staple Crop Productivity in Sidama, Ethiopia.” *Scientific Reports* 15. https://doi.org/10.1038/s41598-025-11880-4.

[21] Gyamfi, Emmanuel Kojo, Samuel Kwesi Asare, Ebenezer Owusu, Daniel Yeboah, and Isaac Kofi Nti. 2024. "Agricultural 4.0 Leveraging on Technological Solutions: Study for Smart Farming Sector." *arXiv*. https://doi.org/10.48550/arXiv.2401.00814.

[22] Happy, K. 2024. "Agricultural Sustainability Through Smart Farming Systems." *Journal of Plant Biotechnology* 51 (18): 167–180. https://doi.org/10.5010/JPB.2024.51.018.167.

[23] IEEP. 2024. "Increasing Climate Change Resilience Through Sustainable Agricultural Practices." Institute for European Environmental Policy. https://ieep.eu/publications/increasing-climate-change-resilience-through-sustainable-agricultural-practices/.

[24] Kabato, W. 2025. "Towards Climate-Smart Agriculture: Strategies for Sustainable Productivity and Resilience." *Agronomy* 15 (3): 565. https://doi.org/10.3390/agronomy15030565.

[25] Katende, Ronald. 2024. "Cross-Country Comparative Analysis of Climate Resilience and Localized Mapping in Data-Sparse Regions." *arXiv*. https://doi.org/10.48550/arXiv.2409.08765.

[26] Klerkx, Laurens, Emma Jakku, and Pierre Labarthe. 2019. "A Review of Social Science on Digital Agriculture, Smart Farming and Agriculture 4.0." *NJAS: Wageningen Journal of Life Sciences* 90–91. https://doi.org/10.1016/j.njas.2019.100315.

[27] Konfo, Tétédé Rodrigue Christian, Rachid Hanna, Hounkonnou Dedehouanou, Jean-Claude Codjia, and Mouhamadou Diagne. 2024. "Recent Climate-Smart Innovations in Agrifood to Enhance Producer Incomes Through Sustainable Solutions." *Journal of Agriculture and Food Research* 18: 100985. https://doi.org/10.1016/j.jafr.2024.100985.

[28] Kulatunga, Chamil, Sahraoui Dhelim, and Tahar Kechadi. 2024. "Machine Learning for Dynamic Management Zone in Smart Farming." *arXiv*. https://doi.org/10.48550/arXiv.2408.00789.

[29] Mishra, Harshit, Pankaj Kumar, Ritu Singh, Ankit Verma, and Neha Sharma. 2025. "The Role of Digital Agriculture in Mitigating Climate Change and Ensuring Food Security: An Overview." In *Climate Resilient and Sustainable Agriculture*, 287–312. https://doi.org/10.1007/978-3-032-04141-8_11.

[30] Mmbando, Gabriel Samuel, Kelvin Mtei, Rehema Mushi, and Athumani Samweli. 2025. "Harnessing Artificial Intelligence and Remote Sensing in Climate-Smart Agriculture." *Cogent Food & Agriculture*. https://doi.org/10.1080/23311932.2025.2454354.

[31] Nawaz, Majid, and Muhammad Inayatullah Khan Babar. 2025. "IoT and AI for Smart Agriculture in Resource-Constrained Environments: Challenges, Opportunities and Solutions." *Discover Internet of Things* 5 (24). https://doi.org/10.1007/s43926-025-00119-3.

[32] Ortiz-Bobea, Ariel, Toby R. Ault, Carlos M. Carrillo, Robert G. Chambers, and David B. Lobell. 2020. "The Historical Impact of Anthropogenic Climate Change on Global Agricultural Productivity." *Nature Climate Change* 11: 306–312. https://doi.org/10.1038/s41558-021-01000-1

[33] Parra-López, Carlos, María del Carmen Carmona-Torres, José Antonio Gómez-Limón, and Francisco José Arriaza. 2024. "Integrating Digital Technologies in Agriculture for Climate Change Adaptation and Mitigation." *Computers and Electronics in Agriculture*. https://doi.org/10.1016/j.compag.2024.109412.

[34] Rafi, Mohamed Shabeer Mohamed, Mehran Behjati, and Ahmad Sahban Rafsanjani. 2025. "Reliable and Cost-Efficient IoT Connectivity for Smart Agriculture: A Comparative Study of LPWAN, 5G, and Hybrid Connectivity Models." *arXiv*. https://doi.org/10.48550/arXiv.2503.11162.

[35] Saiz-Rubio, Verónica, and Francisco Rovira-Más. 2020. "From Smart Farming towards Agriculture 5.0: A Review on Crop Data Management." *Agronomy* 10 (2): 207. https://doi.org/10.3390/agronomy10020207.

[36] Savari, Mohammad. 2025. "Application of the Diffusion of Innovation Theory to Identify Factors Influencing Farmers' Adoption Behavior." *Smart Agricultural Technology*. https://doi.org/10.1016/j.atech.2025.100217.

[37] Seo, Sungjun, and Kooktae Lee. 2025. "Density-Driven Multi-Agent Coordination for Efficient Farm Coverage and Management in Smart Agriculture." *arXiv*. https://doi.org/10.48550/arXiv.2511.12492

[38] Shamshiri, Redmond Ramin, Desa Ahmad, Siva K. Balasundram, Muhammad Shahrimie Mohd Shah, and Cornelia Weltzien. 2024. "Digitalization of Agriculture for Sustainable Crop Production." *Frontiers in Environmental Science* 12. https://doi.org/10.3389/fenvs.2024.1375193.

[39] Sharma, R., et al. 2024. "Artificial Intelligence and IoT-Based Smart Agriculture Systems for Sustainable Farming." *Smart Agricultural Technology* 8: 100524. https://doi.org/10.1016/j.atech.2024.100524

[40] Sharma, Kushagra, and Shiv Kumar Shivandu. 2024. "Integrating Artificial Intelligence and Internet of Things (IoT) for Enhanced Crop Monitoring and Management in Precision Agriculture." *Smart Agricultural Technology* 8: 100292. https://doi.org/10.1016/j.sintl.2024.100292.

[41] Sumartono, E. 2025. "Smart Farming and Precision Agriculture: Leveraging IoT and Data Analytics for Sustainable Agriculture." *International Journal of Food Science and Research*. https://doi.org/10.61796/ijfsr.v1i2.8.

[42] van Dijk, Robin, Anne Godfroy, Elena Nadeu, and Melanie Muro. 2024. *Increasing Climate Change Resilience Through Sustainable Agricultural Practices: Evidence for Wheat, Potatoes and Olives*. Institute for European Environmental Policy. https://doi.org/10.13140/RG.2.2.21459.94244.

[43] Wang, Yifan, Zhiyong Li, Xiaoming Chen, and Haoran Liu. 2024. "Information Fusion in Smart Agriculture: Machine Learning Approaches for Precision Farming." *arXiv*. https://doi.org/10.48550/arXiv.2405.17465..

[44] Wang, Zhaoan, et al. 2025. "Developing and Integrating Trust Modeling into Multi-Objective Reinforcement Learning for Intelligent Agricultural Management." *arXiv*. https://doi.org/10.48550/arXiv.2505.10803.

[45] Wu, P. 2025. "Artificial Intelligence in Sustainable Agriculture: Towards a Smart and Resilient Farming Future." *Smart Agricultural Technology*. https://doi.org/10.1016/j.atech.2025.100809.

[46] World Bank. 2024. "Climate-Smart Agriculture." World Bank. https://www.worldbank.org/en/topic/climate-smart-agriculture.

[47] Xu, Zhuoning, Jian Xu, Mingqing Zhang, Peijie Wang, Chao Deng, and Cheng-Lin Liu. 2025. "Multimodal Agricultural Agent Architecture (MA3): A New Paradigm for Intelligent Agricultural Decision-Making." *arXiv*. https://doi.org/10.48550/arXiv.2504.04789

[48] Yar, Fayaz Gul Mazloum, and Mohammad Edris Naderi. 2025. "Smart Rural Development: Using Information Technology for Sustainable Rural Planning." *Eduvest Journal of Universal Studies* 5 (2): 3277–3286.