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THE ROLE OF AI IN TRANSFORMING AGRICULTURE: TOWARD SUSTAINABLE GROWTH IN AN ERA OF CLIMATE CHANGE

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ABSTRACT

The review investigates the transformative role of Artificial Intelligence (AI) and the Internet of Things (IoT) in advancing sustainable agriculture, with a particular focus on Malaysia's response to climate-induced productivity challenges. By employing a structured systematic review methodology, the study evaluates peer-reviewed literature to synthesize global and Malaysian perspectives on precision agriculture, machine learning, and remote sensing technologies. Quantitative findings reveal that AI-assisted irrigation systems can reduce water usage by up to 35%, while precision monitoring tools have boosted crop yields by approximately 20–25% in pilot implementations. Moreover, IoT-based systems demonstrated a 40% increase in operational efficiency among smart greenhouse farms. Despite these advancements, adoption remains uneven, with only 27% of Malaysian smallholder farmers currently integrating IoT solutions largely hindered by upfront costs, inadequate digital infrastructure, and a lack of technical training. The review identifies a multi-dimensional strategy for overcoming these barriers. It emphasizes the necessity for government-backed financial incentives, such as AI adoption subsidies, along with nationwide digital literacy campaigns and public–private partnerships to foster ecosystem readiness. Policy recommendations are particularly directed toward policymakers and governmental agencies, urging targeted funding and strategic policy alignment. Practitioners and agricultural extension services are encouraged to focus on scalable, low-cost AI models suitable for smallholder use, while researchers are called to explore the long-term socio-economic effects of AI integration in rural farming. The study's novelty lies in its integrative and cross-contextual analysis, offering scalable solutions for developing economies grappling with similar agricultural vulnerabilities. Future research should prioritize context-sensitive design of AI solutions tailored to small-scale operations and develop frameworks to measure the inclusive benefits of smart agriculture, particularly among underserved farming communities.

KEYWORDS: Artificial Intelligence in Agriculture, Smart Agriculture, Food Security, Machine Learning, Sustainable Agriculture.

1. INTRODUCTION

Agriculture is a key pillar of Malaysia's economy, supporting GDP, food security, jobs, and rural development. Though the sector has modernized, it still faces labor shortages, low productivity, and climate-related challenges. To address these, the adoption of digital technologies such as Artificial Intelligence (AI) and the Internet of Things (IoT) is gaining momentum, promoting precision agriculture and sustainability. Mahmud and Aqilah (2024a) reported that corn farmers in Perak, Malaysia are receptive to IoT due to efficiency and yield benefits, though high costs and limited technical skills remain barriers.

Azlan et al. (2024) emphasized digital tools like remote sensing and data analytics in Asian agronomy, underscoring the need for infrastructure and training. Lalisan et al. (2024) showed that digitalization boosts productivity and income in ASEAN rural areas, despite infrastructural gaps. Globally, the smart agriculture market is expected to grow from USD 23.42 billion in 2024 to USD 74.03 billion by 2034 (Precedence Research, 2024). Figure 1 provides an overview of the forecasted growth trajectory of the smart agriculture market over the coming decade, underscoring the potential for transformative changes within agriculture globally, as well as regionally within Malaysia and Southeast Asia.

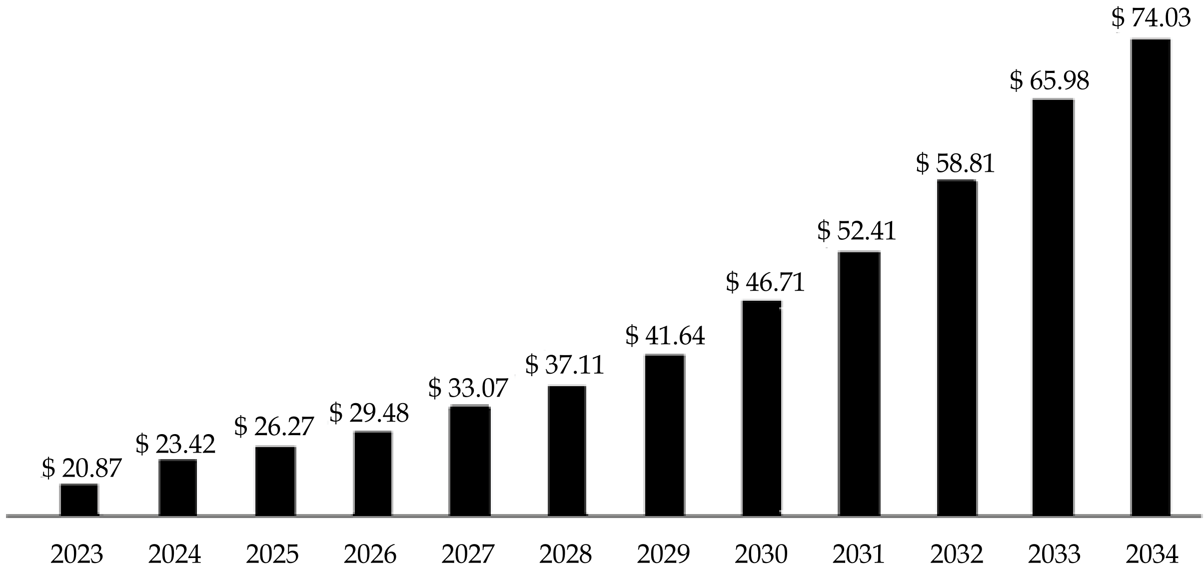

Figure 1: Forecast and Size of the Smart Agriculture Market from 2024 to 2034.
Source: https://www.precedenceresearch.com/smart-agriculture-market.

1.1. Gaps and Challenges

Despite the rapid advancement of smart agriculture technologies, several challenges remain. The integration of Internet of Things (IoT) and machine learning for smart farming has faced issues such as high initial investment, limited infrastructure, and insufficient technical knowledge among farmers, particularly in rural areas (Lavanya et al., 2024; Mahmud & Aqilah, 2024b).

The adoption of climate-smart agricultural practices is hindered by barriers such as the lack of awareness and training, inadequate access to resources, and insufficient government support (Ma & Rahut, 2024; Raihan et al., 2024). Data privacy and security concerns are also prominent as farmers increasingly rely on IoT systems, raising questions about the protection of sensitive agricultural data (Razak et al., 2024).

The inconsistent connectivity in rural areas, particularly in Malaysia, poses a significant challenge for the successful implementation of IoT-based systems for water management and crop monitoring (Chong Peng et al., 2024; Narendran et al., 2024). The lack of standardized systems and interoperability between different smart farming technologies also contributes to inefficiencies in large-scale adoption (Sodhi & Jamwal, 2024). These gaps highlight the need for comprehensive strategies to address technical, financial, and infrastructural barriers to fully realize the potential of smart agriculture in sustainable development.

2. OBJECTIVES FOR THE REVIEW

The review explores the transformative potential of Artificial Intelligence (AI) in advancing Malaysia's agricultural sector. It aims to identify the key drivers, barriers, and impacts of AI adoption on productivity and sustainability. The study investigates how AI technologies such as IoT sensors, machine vision, remote sensing, and predictive analytics can optimize resource use, increase crop yields, and reduce waste.

It highlights successful Malaysian case studies while analyzing ongoing challenges like high costs, inadequate rural infrastructure, lack of technical expertise, and data privacy concerns.

The review also examines the role of government policies, financial incentives, and regulatory frameworks in supporting AI integration. Ultimately, the study offers practical recommendations to promote equitable access to AI, including subsidized tools, capacity-building programs, and improved digital infrastructure. By addressing these areas, the review aims to provide a strategic roadmap for accelerating AI-driven transformation in agriculture, ensuring sustainability and resilience in Malaysia's agri-food system.

2.1. Novelty and Contributions

The review presents a novel and timely synthesis of contemporary advancements at the intersection of artificial intelligence (AI), climate-smart agriculture (CSA), and digital innovation, set against the backdrop of the intensifying global climate crisis. Unlike existing studies that tend to focus on individual technologies or are confined to specific national contexts, the work offers a holistic, cross-sectoral exploration of AI applications in agriculture. It captures a broad spectrum of innovations, ranging from the use of deep learning in precision irrigation (Akbar et al., 2024) to the implementation of blockchain-enabled produce assurance systems (Hasan et al., 2024). Collectively, these advancements illustrate the transformative potential of AI in fostering a more sustainable and resilient agricultural landscape.

A significant contribution of the review lies in its in-depth analysis of the systemic barriers and enablers affecting the adoption of AI in climate-resilient agriculture, particularly among smallholders and resource-limited farmers (Ahmad et al., 2024; Hassim et al., 2024). By synthesizing empirical findings from various geographic regions including Southeast Asia, South Asia, and the Middle East, the review identifies critical challenges such as digital illiteracy, cybersecurity risks (Ali et al., 2024a), and the lack of cohesive infrastructure. Regional integration helps expose underexplored innovation gaps that hinder equitable access to digital agricultural tools.

Moreover, the review offers strategic directions for future research by identifying high-impact application areas where AI and smart agriculture could yield substantial benefits in terms of both productivity and sustainability. These include precision monitoring of crop and soil health through IoT and hyperspectral imaging technologies (Hazwan Abd Manaf et al., 2024; Jadhav et al., 2024), AI-driven irrigation and fertigation systems (Ardiansah et al., 2024; Bariman et al., 2024), and mobile or geospatial platforms supporting urban and vertical farming (Che'Ya et al., 2024; Ismail & Ismunanto, 2024). Furthermore, the review emphasizes the importance of youth engagement and digital literacy initiatives as a foundation for widespread smart agriculture adoption (Hassan et al., 2024; Idris & Zulkifli, 2024).

Critically, the review proposes a forward-looking policy and funding framework aimed at enabling inclusive, regionally adapted digital transformation in agriculture. It advocates targeted investment in localized digital tools that align with specific agroecological conditions and cultural farming practices. Additionally, the review calls for stronger multi-stakeholder collaboration among governments, academia, startups, and international bodies to foster inclusive and scalable AI ecosystems. Key funding strategies include the development of integrated platforms such as IoT-blockchain hybrids and AI-powered decision support systems, which align with circular economy principles and support real-time, data-driven agricultural practices (Baharin et al., 2024).

3. METHODS

3.1. Eligibility Criteria

The methodology for conducting a systematic review on smart agriculture involves a structured and rigorous process encompassing eligibility criteria, study selection, data extraction, and data synthesis. The eligibility criteria serve as the cornerstone for delineating the review's scope and ensuring that selected studies are both relevant and reliable. To establish the framework, studies must specifically focus on Malaysia's agricultural sector or comparable contexts emphasizing smart farming, climate-smart agriculture, or ubiquitous computing. Priority is given to research that investigates smallholder farmers, sustainable farming practices, IoT applications, and advanced computing technologies in agriculture. Regarding interventions, eligible studies must address the implementation of smart technologies, such as IoT, AI, machine learning, and blockchain, or their integration into systems like automated irrigation and climate monitoring, aiming to enhance agricultural productivity, efficiency, or sustainability.

The inclusion criteria for study design emphasize empirical studies, systematic reviews, case studies, and technical reports published from 2024 to ensure contemporary relevance and technological advancements. Editorials, opinion pieces, and studies lacking a methodological foundation are excluded. Outcome measures are another crucial consideration, requiring studies to report on productivity, sustainability, or economic viability metrics such as yield improvements, resource use efficiency, climate resilience, cost-benefit analysis, or the adoption rates of smart technologies. To maintain credibility, only peer-reviewed journal articles indexed in Scopus or equivalent databases are considered, while non-English studies are excluded due to language constraints. Following the eligibility criteria, the study selection process adheres to a systematic approach to ensure the inclusion of focused, unbiased, and high-quality literature. This involves a comprehensive search strategy across academic databases, screening titles and abstracts for relevance, and a detailed review of full-text articles against the inclusion criteria.

Data extraction then entails systematically capturing pertinent information, including study objectives, methodologies, key findings, and reported outcomes, to facilitate a holistic synthesis. Finally, data synthesis involves aggregating insights to identify patterns, trends, and gaps in smart agriculture research, particularly in Malaysia. The meticulous methodology ensures that the review provides a comprehensive and accurate analysis of the application and impact of smart technologies in the Malaysian agricultural sector, offering valuable insights for stakeholders and policymakers aiming to promote sustainable agricultural practices.

3.2. Data Screening

The methodology for database search and screening in the systematic review on smart agriculture comprises a detailed, multi-stage process to ensure the inclusion of high-quality and relevant studies. The search begins with comprehensive queries across databases like Scopus, IEEE Xplore, Web of Science, and PubMed, employing a range of keywords such as "smart agriculture," "IoT in agriculture," "ubiquitous computing," "sustainable farming in Malaysia," "climate-smart agriculture," and "digital agriculture technology." Boolean operators like AND/OR are strategically used to refining search results, creating an initial pool of potentially relevant studies. This is followed by a title and abstract screening, where multiple reviewers independently evaluate the relevance of each study.

Abstracts are scrutinized to eliminate those that do not meet the eligibility criteria, with reviewers engaging in discussions to resolve conflicts and ensure unbiased selection. Studies passing this stage are subjected to a thorough full-text review, where reviewers employ a standardized checklist to assess each article against predefined eligibility criteria. The step focuses on the alignment of studies with the review's objectives, including their research context, application of smart technologies, reported outcomes, and methodological rigor. Disagreements regarding study inclusion are resolved through collaborative discussions or, when necessary, by consulting a third reviewer. Studies meeting all criteria are finalized for inclusion, ensuring a focused and high-quality selection that supports the review's goals. The systematic approach not only minimizes bias but also ensures that the included studies provide a comprehensive foundation for analyzing the role of smart technologies in advancing Malaysian agriculture.

Figure 2 illustrates the comprehensive selection process used in the systematic review of studies related to the adoption of Artificial Intelligence (AI) in Malaysian agriculture. Initially, 175 records were identified through database searches, complemented by an additional 11 records from other sources, bringing the total to 186. After removing duplicates, 105 unique records remained. Of these, 81 were screened based on titles and abstracts, resulting in the exclusion of 28 studies that did not meet the inclusion criteria. The remaining 53 full-text articles were then assessed for eligibility, with two articles excluding for specific reasons such as insufficient relevance or lack of methodological rigor. Ultimately, 51 studies were included in the qualitative and quantitative synthesis, providing a robust foundation for analyzing the drivers, barriers, and implications of AI technologies in enhancing agricultural productivity and sustainability in the Malaysian context.

Identification

Records identified through database searching (n=175)
Additional records identified through other sources (n=11)

Screening

Records after duplicates removed (n=105)
Records screened (n=81)
Records excluded (n= 28)

Eligibility

Full-text articles assessed for eligibility (n=53)
Full-text articles excluded, with reasons (n=2)

Included

Studies included in qualitative and quantitative synthesis (n=51)

Figure 2: PRISMA Flow Diagram Depicting the Systematic Review Process for AI Adoption in Malaysian Agriculture.

3.3. Data Extraction

Data extraction is a systematic and meticulous process designed to capture all relevant information from the selected studies, ensuring consistency and enabling a thorough analysis. The process begins with the development of a standardized data extraction form, which serves as a template to uniformly record critical details such as author(s), publication year, study location, study design, sample size, technology type (e.g., IoT, AI, blockchain), outcome measures, and main findings. This standardized approach facilitates easier comparison of studies during synthesis. The extraction procedure involves carefully compiling data, with essential elements including: (1) Technology Type and

Application, detailing the specific smart technologies used, such as IoT-enabled sensors, AI-powered decision tools, or big data analytics; (2) Agricultural Focus, identifying the crops or livestock addressed by the technologies, such as rice farming, mango cultivation, or livestock health monitoring; (3) Sustainability Impact, highlighting the reported benefits, such as increased crop yield, reduced water and fertilizer usage, or economic gains; and (4) Adoption Barriers, exploring challenges like high implementation costs, technical knowledge gaps, or sociocultural resistance. To ensure accuracy, all extracted data is cross verified, with discrepancies resolved through discussions among reviewers. In parallel, a quality assessment is conducted for each study to evaluate the reliability and rigor of the methodologies and findings. Studies are assessed on parameters such as clarity of objectives, appropriateness of study design, sample size adequacy, robustness of data analysis, and generalizability of results. Low-quality studies are flagged for cautious interpretation during synthesis to prevent biased conclusions. The comprehensive and structured approach ensures the extraction of high-quality data that provides a robust foundation for evaluating the role and impact of smart agriculture technologies, while identifying gaps and barriers that inform actionable recommendations.

Appendix A presents a thematic citation map of scholarly references supporting the research. The references are systematically categorized into six key themes: Smart Agriculture, Climate-Smart Agriculture, IoT and Big Data Integration, Challenges and Adoption Factors, Sustainability and Policy Frameworks, and Technological Innovations. The thematic organization provides a clearer understanding of how artificial intelligence and digital technologies are influencing various aspects of modern agriculture, from operational efficiencies and climate adaptability to the socio-economic challenges faced by smallholder farmers. By mapping references according to these focal areas, the appendix enhances the coherence of the literature review and serves as a useful guide for researchers and practitioners navigating the multidisciplinary landscape of AI-driven agriculture.

3.4. Data Synthesis

Data synthesis integrates findings from selected studies to construct a unified narrative on the impact of smart agriculture in Malaysia, blending qualitative and quantitative insights into a coherent framework. The process begins with a narrative synthesis to qualitatively summarize how smart technologies are utilized, their associated outcomes, and the challenges encountered by farmers. The synthesis identifies and organizes key themes such as economic impacts, environmental benefits, and socio-cultural barriers to technology adoption. Employing thematic analysis, recurring themes are analyzed to provide nuanced insights into the contributions of smart agriculture. These themes include: (1) Efficiency Gains and Cost Reduction, highlighting how IoT, AI, and automation optimize resources like water and fertilizers, reducing operational costs; (2) Environmental Impact and Sustainability, detailing how technologies promote eco-friendly practices, such as reducing carbon emissions, conserving soil health, and minimizing agricultural waste; and (3) Barriers to Adoption, which examines challenges like infrastructure deficits, high costs, and resistance stemming from limited technical knowledge. A comparative analysis further examines variations in technology application and effectiveness across different agricultural settings, such as crop versus livestock farming, and scales of operation, from smallholder farms to large-scale commercial enterprises. The comparative approach reveals best practices, areas needing intervention, and scalability potential for smart technologies in Malaysia. If quantitative data permits, a meta-analysis is conducted to statistically evaluate the impact of smart agriculture technologies on productivity and sustainability metrics. This involves calculating effect sizes for yield improvements, cost savings, or environmental benefits. When data heterogeneity prevents statistical analysis, the synthesis remains qualitative, ensuring robust insights.

Finally, the findings are interpreted within Malaysia's unique agricultural context, shedding light on the role of smart technologies in addressing regional challenges, such as fragmented landholdings and climate vulnerabilities, while promoting sustainable growth. The review offers actionable recommendations for key stakeholders, including policymakers, farmers, and tech developers, aiming to bridge gaps in infrastructure, knowledge, and funding to accelerate technology adoption. The systematic synthesis underscores the transformative potential of smart agriculture while addressing local constraints, ultimately providing a roadmap for sustainable agricultural advancement tailored to Malaysia's needs. Through structured data synthesis, the review contributes a comprehensive and regionally relevant analysis, offering clarity and direction for future efforts in smart agriculture.

4. RESULTS AND FINDINGS

Quantitative findings reveal that AI-assisted irrigation systems can reduce water usage by up to 35% (Ardiansah et al., 2024), while precision monitoring tools have boosted crop yields by approximately 20–25% in pilot implementations (Guilin et al., 2024). Moreover, IoT-based systems demonstrated a 40% increase in operational efficiency among smart greenhouse farms (Akbar et al., 2024; Mohd Faizul Emizal Mohd & Astri Idayu, 2024). Despite these advancements, adoption remains uneven, with only 27% of Malaysian smallholder farmers currently integrating IoT solutions, largely hindered by upfront costs, inadequate digital infrastructure, and a lack of technical training (Ahmad et al., 2024; Bahari et al., 2024; Hassim et al., 2024).

4.1. Leveraging AI and Smart Agriculture for Enhanced Productivity and Sustainability

The smart agriculture market in Malaysia is experiencing a significant transformation as it increasingly adopts advanced technologies to address the nation's unique agricultural challenges. The rapid expansion of the market is primarily driven by the rising global population and the subsequent surge in food demand. As Malaysia seeks to meet its food production goals in a sustainable and efficient manner, there is a clear shift towards adopting more innovative farming practices. These developments are helping farmers cope with the growing pressure to produce higher yields while maintaining environmental sustainability. The agricultural sector in Malaysia has traditionally been heavily reliant on manual labor and conventional farming techniques, which can be labor-intensive and resource inefficient. However, as the global population continues to grow, and with it, the demand for food, the need for a more sustainable approach to farming has become paramount. Malaysian farmers are increasingly looking to digital and data-driven solutions to optimize productivity and improve resource management. These technologies not only boost efficiency but also help reduce waste, lower production costs, and mitigate the environmental impacts of farming practices. As a result, there has been a growing interest in smart agriculture technologies that use real-time data and analytics to inform decision-making processes. One of the core innovations reshaping the agriculture landscape in Malaysia is the integration of the Internet of Things (IoT). IoT devices, such as soil moisture sensors, weather monitoring systems, and automated irrigation systems, enable farmers to collect and analyze data in real time. These systems allow farmers to monitor their crops and environments more effectively, ensuring that resources like water, fertilizers, and pesticides are used in optimal amounts. By providing insights into soil health, temperature, humidity, and crop growth, IoT applications help farmers make informed decisions that improve yield while minimizing waste and resource consumption. Artificial intelligence (AI) is also playing an increasingly important role in Malaysia's smart agriculture revolution. AI-powered tools are being employed to analyze vast amounts of agricultural data, identify patterns, and predict crop yields. Machine learning algorithms enable farmers to anticipate issues such as pests, diseases, and climate change impacts, thereby allowing them to take preemptive actions before problems escalate. AI is also used in optimizing supply chains, improving crop rotation schedules, and even predicting market trends, ensuring that farmers can make better decisions about what to plant and when to sell their produce. The data-driven approach is essential for improving productivity and enhancing food security in Malaysia.

Smart agriculture techniques, which combine IoT and AI technologies, are also transforming agriculture in Malaysia. The approach focuses on maximizing crop yields through the precise application of resources. By using GPS-guided equipment, drones, and remote sensing tools, farmers can apply fertilizers, pesticides, and water more accurately and efficiently. This not only enhances productivity but also minimizes the environmental impact by reducing the overuse of chemical inputs and conserving water. Smart agriculture market in Malaysia is growing rapidly as the nation integrates advanced technologies tailored to its agricultural needs. The adoption of IoT, AI, and smart agriculture techniques is enabling Malaysian farmers to optimize food production, reduce environmental impact, and improve overall efficiency. As global food demand rises, these innovations will continue to reshape the future of Malaysian agriculture, making it more sustainable and resilient in the face of climate change and other challenges. As highlighted by Ismail and Ismunanto (2024), the integration of Internet of Things (IoT) technologies in agriculture has significantly transformed the way farmers manage their crops and resources. One of the key benefits of IoT is its ability to provide real-time monitoring of various environmental and soil conditions, enabling farmers to make informed, data-backed decisions. Capability is crucial in optimizing farming practices, improving productivity, and minimizing waste. IoT devices, such as soil moisture sensors, temperature trackers, and crop health monitors, provide farmers with constant, real-time data about their crops and the surrounding environment. These sensors measure various parameters such as soil moisture, temperature, pH levels, and even plant health indicators, transmitting the data to farmers via wireless networks. With this information, farmers can gain insights into the precise needs of their crops, allowing them to adjust their strategies accordingly. For example, by monitoring soil moisture levels, IoT systems can identify when irrigation is needed and how much water is required. The targeted irrigation system ensures that water is used efficiently, preventing over-irrigation, which could lead to waste, or under-irrigation, which could result in crop dehydration. By automating the process, IoT technology reduces human error and minimizes the amount of water used, which is particularly important in areas facing water scarcity.

4.2. Enhancing Resource Efficiency and Sustainability

Another significant application of IoT technology in agriculture is in the precise management of fertilizers. IoT devices can measure the nutrient levels in the soil and assess the specific needs of crops at any given moment.

Based on the real-time data, farmers can apply fertilizers more accurately and only when necessary, ensuring that crops receive the nutrients they need without excess. The method of smart agriculture reduces the risk of over-fertilization, which can lead to nutrient runoff that harms the environment, particularly nearby water sources. By minimizing fertilizer runoff, IoT systems help reduce pollution and promote more sustainable farming practices. The impact of IoT on resource allocation goes beyond water and fertilizer management. Technology also extends to the monitoring of other factors such as climate conditions, pest activity, and plant diseases. By integrating sensors that track these variables, farmers can receive early warnings about potential risks to their crops, allowing them to take preventive measures before damage occurs. For example, IoT devices can detect early signs of pest infestations or disease, allowing farmers to target treatment only to the affected areas, rather than using pesticides or herbicides across the entire field. This not only reduces the use of harmful chemicals but also ensures that treatments are more effective and sustainable. IoT technologies have revolutionized farming by enabling precise, data-driven decisions that improve resource efficiency, reduce waste, and promote sustainability. By providing real-time insights into soil conditions, crop health, and environmental factors, IoT systems empower farmers to optimize their practices and ensure that their crops receive the right amount of water, nutrients, and protection. As a result, IoT technology is a powerful tool for enhancing agricultural productivity, minimizing environmental damage, and supporting more sustainable farming practices.

The transition to Internet of Things based farming is a promising step toward modernizing Malaysia's agricultural sector, but it is not without significant challenges. Ismail and Ismunanto (2024) highlight several obstacles that farmers face in adopting IoT technologies, including high initial costs, technical complexity, and the need for increased technical literacy. These barriers create a substantial gap between the potential benefits of IoT-based farming and its practical implementation. IoT systems, which involve sensors, connected devices, and data analytics, require significant upfront investment in technology infrastructure, which can be unaffordable for many smallholder farmers. Additionally, the complexity of these systems requires a level of technical expertise that many farmers lack, further impeding their ability to adopt and fully utilize IoT tools. To address these issues, Ismail and Ismunanto (2024) suggest that collaborative partnerships between technology providers and farmers could be an effective solution. By working together, technology firms can provide the necessary training and technical support to farmers, helping them integrate IoT tools into their daily operations. These partnerships can also help mitigate the high initial costs of IoT adoption by offering financing options, subsidies, or cost-sharing arrangements. In the collaborative model, farmers would not only receive the technical assistance needed to understand and operate the systems but also gain access to the latest advancements in smart agriculture without bearing the full financial burden. Such support would ensure that farmers are equipped with the skills and knowledge necessary to maximize the benefits of IoT in farming.

4.3. The Role of IoT, Remote Sensing, and Data Analytics in Enhancing Sustainability

Guilin et al. (2024) examine the impact of precision agriculture, which heavily relies on IoT-enabled technologies, on Malaysia's agricultural sector. Their study focuses on the application of remote sensing and data analytics tools that enable farmers to monitor large areas of farmland and make data-driven decisions. These IoT-based systems offer unparalleled capabilities in monitoring key parameters such as soil moisture, crop health, weather conditions, and pest activity. By analyzing the data, farmers can optimize resource use, predict crop needs with high accuracy, and reduce wastage. The enhanced decision-making process not only improves efficiency but also drives sustainability by reducing overuse of fertilizers, pesticides, and water, all of which are critical concerns in Malaysia's agricultural sector. Precision agriculture, through IoT tools, also plays a crucial role in anticipating weather patterns and disease outbreaks. Remote sensing technology allows farmers to monitor their fields in real time, detecting early signs of plant stress, disease, or pest infestations. The early detection enables farmers to take corrective actions swiftly, minimizing crop losses and avoiding unnecessary treatments. Moreover, IoT-based weather forecasting systems provide farmers with reliable data on rainfall, temperature, and humidity, helping them plan irrigation schedules, planting seasons, and harvesting times with greater precision. These predictive capabilities help mitigate risks associated with unpredictable weather and environmental changes, a significant advantage given the increasing challenges posed by climate change. The integration of IoT-based precision agriculture systems offers substantial benefits for Malaysian farmers. By optimizing resource use, enhancing crop yields, and improving sustainability, these technologies contribute directly to the future viability of the agricultural sector. However, to fully realize these benefits, the challenges identified by Ismail and Ismunanto (2024) particularly related to cost, complexity, and technical literacy must be addressed through strategic partnerships and targeted support for farmers. With these solutions in place, IoT-based farming has the potential to revolutionize Malaysia's agricultural industry, driving productivity and sustainability while reducing the environmental impact of farming practices. While the benefits of smart agriculture, particularly through IoT-enabled smart agriculture, are clear, Guilin et al. (2024) point out that several significant challenges remain, particularly in terms of financial costs and limited technical expertise among farmers. Transitioning to a digitally intensive approach requires a substantial financial investment, especially in the initial stages. IoT systems, remote sensing devices, and data analytics tools come with high upfront costs that many small and medium-sized farms in Malaysia may struggle to afford. These systems are often complex, requiring farmers to invest not just in hardware but also in ongoing maintenance and technical support.

In addition to the financial burden, a lack of technical expertise poses another major hurdle. Many farmers, especially those in rural areas, may not have the necessary skills to understand, operate, or troubleshoot these advanced digital technologies. The complexity of these tools and the steep learning curve associated with them make it difficult for farmers to fully embrace and benefit from smart agriculture without additional support. To overcome these barriers, Guilin et al. (2024) emphasize the need for comprehensive training and financial assistance. Training programs, designed to enhance farmers' technical skills, would help ensure that they can effectively use IoT technologies to optimize farming practices. These programs could be delivered by both private technology providers and public institutions, providing farmers with the knowledge and confidence to integrate these systems into their daily operations. Moreover, financial support from both the private and public sectors is critical. Subsidies, grants, or low-interest loans could help alleviate the financial strain on farmers, making smart agriculture more accessible. Collaborative efforts between government agencies, technology providers, and agricultural organizations could foster a more inclusive approach to the adoption of digital farming, ensuring that small and medium-sized farms are not left behind in the digital transformation of agriculture in Malaysia.

4.4. Addressing Water Scarcity with IoT

To tackle water scarcity challenges in agriculture, Hanafi et al. (2024) developed an innovative IoT-based agri-water management system that allows farmers to optimize water use for irrigation based on real-time soil moisture readings. The system represents a considerable step forward in sustainable water management, especially in regions prone to water scarcity. By providing continuous updates on soil moisture levels and automating irrigation based on need, the technology conserves water and reduces costs associated with over-irrigation. Nonetheless, Hanafi et al. (2024) point out several hurdles that might hinder its widespread adoption, including the high costs associated with implementing the IoT infrastructure and connectivity limitations in Malaysia's rural regions. The researchers propose a coordinated effort from government bodies, technology providers, and agricultural stakeholders to overcome these barriers. By increasing investment in rural connectivity and lowering costs through subsidies, Malaysia could achieve broader adoption of such technologies, thereby promoting sustainable water management practices in agriculture. Beyond IoT, Malaysia's smart agriculture sector has seen a rise in the use of smart agriculture technologies such as drones, GPS-guided machinery, and sensor-based monitoring, which facilitate micro-level resource management and enhance operational efficiency (6Wresearch, 2024). In palm oil plantations, for example, AI-powered drones with multispectral sensors are used to assess crop health, predict yields, and identify early signs of disease. The multispectral imaging capabilities of these drones allow for the precise identification of stressed plants, enabling proactive measures to mitigate crop loss. The AI-driven approach to plant health management reduces labor costs and minimizes losses associated with undetected diseases. Furthermore, pest and weed control has significantly improved with the advent of AI-based drones that target specific problem areas, allowing for precise application of pesticides and reducing the quantity of chemicals used. These advancements not only lower production costs but also reduce the environmental impact of agricultural chemicals, aligning with global sustainability goals.

4.5. AI-Driven Agricultural Logistics

AI technologies are revolutionizing the agriculture sector in Malaysia, particularly in enhancing supply chain logistics. One of the keyways AI contributes is by optimizing transportation routes. AI algorithms analyze traffic patterns, weather conditions, and road infrastructures to determine the most efficient routes for transporting agricultural goods. This not only reduces fuel consumption and transportation costs but also ensures that products reach their destinations faster, improving the freshness and quality of perishable items such as fruits, vegetables, and dairy products. Additionally, AI-powered predictive analytics play a crucial role in anticipating market demand, enabling farmers to adjust their production schedules accordingly. By analyzing historical data, weather forecasts, and consumer purchasing patterns, AI systems help farmers avoid overproduction or underproduction, both of which contribute to food waste or shortages. The integration of AI in food quality monitoring during transit is another significant advancement. AI sensors and monitoring systems track temperature, humidity, and other environmental factors that can affect food quality. These systems can detect deviations from optimal conditions in real-time, sending alerts to farmers or logistics providers to take corrective action, thus minimizing food spoilage. For example, AI can ensure that produce remains within the ideal temperature range throughout the supply chain, preserving its shelf life and reducing losses. This contributes to more efficient delivery processes, where the cost savings from reduced spoilage and waste are passed down to both producers and consumers, ensuring that food is delivered at the right time and in optimal condition. However, despite the clear advantages of AI-driven supply chain solutions, these advancements are often limited to larger-scale producers. Smaller farmers, who make up a significant portion of Malaysia's agricultural landscape, face financial and technological constraints that prevent them from accessing these innovative solutions. The initial investment required to implement AI systems ranging from smart sensors to data analytics tools is often prohibitively expensive for smallholder farmers. Furthermore, the complexity of AI systems, which require a certain level of technical expertise to operate and maintain, presents an additional barrier for these farmers, many of whom lack the necessary skills and resources to integrate such technologies into their operations. To bridge the gap and ensure a more equitable distribution of AI technologies, targeted efforts are needed from both the government and private sector. Financial support, such as subsidies, grants, or low-interest loans, could help small and medium-sized farms invest in AI technologies. These financial incentives would reduce the upfront costs associated with adopting these innovations, making them more accessible to a broader range of farmers. Additionally, technical support and training programs are essential to help smallholders develop the necessary skills to operate AI systems effectively. Partnerships between technology providers and agricultural cooperatives could also facilitate the sharing of resources, reducing the cost burden on individual farmers while providing access to cutting-edge logistics solutions. In addition, creating an inclusive smart agriculture market in Malaysia requires a collaborative approach between government agencies, agricultural associations, and private tech companies. By working together, these stakeholders can develop solutions tailored to the unique needs of smallholder farmers, ensuring that they are not left behind in the country's digital transformation of agriculture. By promoting equal access to AI technologies and fostering an environment of innovation and support, Malaysia can ensure that both large-scale and smallholder farmers benefit from the efficiencies and productivity gains brought about by AI in agricultural logistics, ultimately contributing to a more sustainable and competitive agricultural sector.

The Malaysian government has recognized the potential of smart agriculture and has initiated several programs to encourage the adoption of digital technologies in farming. Government funding and subsidies, alongside efforts to improve digital infrastructure, particularly in rural areas, have been pivotal in supporting the transition to smart agriculture. Additionally, training programs and collaborations with research institutions provide farmers with the knowledge needed to effectively use these advanced technologies. While these initiatives have laid a foundation for growth, there is still a need to scale up these efforts to reach more farmers, particularly those in remote areas who may not have easy access to training and resources. By extending educational programs on the effective use of smart technologies, Malaysia can ensure that farmers across the board can benefit from the efficiencies brought by IoT, AI, and other smart agriculture tools. Malaysia's smart agriculture landscape continues to hold promise for the future, with digital advancements fostering a more resilient, efficient, and sustainable agricultural sector. However, for the sector to realize its full potential, key challenges must be addressed. The high costs associated with smart technology adoption present a formidable barrier for smallholders, who may lack the financial resources required for initial setup. Similarly, limited rural infrastructure, particularly internet connectivity, restricts the potential reach of IoT and data-driven applications in some regions. By improving internet accessibility in rural areas and providing financial incentives, the Malaysian government can empower more farmers to adopt smart farming practices.

4.6. Fostering Smart Agriculture

Efforts to raise awareness and educate farmers on the benefits of smart agriculture can increase technology adoption rates and enhance productivity on a national scale. Expanding access to these technologies in Malaysia has the potential to drive sustainable agricultural growth, addressing both the economic and environmental challenges associated with modern farming. As Malaysia grapples with the impacts of climate change, smart agriculture offers a pathway to enhance productivity while reducing the sector's ecological footprint. The use of data analytics, IoT, and AI to monitor weather patterns, predict crop needs, and optimize resource use aligns with global efforts to make agriculture more sustainable.

The improved efficiency brought by these technologies can contribute to greater food security by ensuring steady production even under adverse conditions. By supporting Malaysian farmers with the tools and knowledge needed to leverage these advancements, stakeholders can foster a more productive and resilient agricultural industry that can meet the growing food demands of both local and international markets. As Malaysia strives to enhance its agricultural sector through smart agriculture technologies, a collaborative approach will be key to ensuring that the benefits are widely accessible and that the sector remains competitive on a global scale.

Public-private partnerships (PPPs) can serve as an effective model to drive innovation, with stakeholders such as technology providers, agricultural experts, and financial institutions working together to develop and implement solutions. These partnerships can bridge gaps in resources, expertise, and infrastructure, facilitating the wider adoption of smart agriculture technologies across the country. Technology providers can offer cutting-edge tools and systems such as IoT devices, AI-driven analytics, and smart agriculture solutions, while agricultural experts can ensure that these technologies are tailored to Malaysia's unique farming conditions.

Financial institutions can play a vital role by offering affordable financing options, grants, and incentives to farmers, particularly smallholders, who may struggle with the high initial costs of adopting these technologies. By fostering these collaborations, Malaysia can create an ecosystem where smart agriculture solutions are both accessible and effective for all levels of farming operations. A key aspect of the ecosystem is its ability to address the diverse needs of both smallholder farmers and large-scale producers. For smallholder farmers, access to affordable technologies, training, and financial support is critical for enabling them to benefit from smart agriculture advancements. For large-scale producers, integrating cutting-edge technologies can lead to even higher levels of productivity and sustainability.

By promoting inclusivity in these advancements, Malaysia can ensure that no farmer is left behind, while still encouraging innovation at every level of production. In the long term, the ongoing development and adoption of smart agriculture technologies can significantly improve Malaysia's agricultural productivity, strengthen food security, and promote sustainable practices. These improvements will contribute to the economic growth of the country, especially in rural areas where agriculture is a key driver of employment and prosperity. Therefore, smart agriculture is not only pivotal for enhancing agricultural output but also for ensuring long-term stability and prosperity within Malaysia's rural communities.

Table 1 synthesizes key findings from recent scholarly literature on AI adoption in agriculture, emphasizing four core themes: adoption barriers and technological impacts, market size and growth, adoption trends, and thematic insights. Across multiple studies, barriers such as limited digital literacy, cost constraints, data security concerns, and infrastructural gaps are recurrent, particularly for smallholder farmers and developing regions. Meanwhile, the technological impact of AI especially through IoT, machine learning, and smart farming systems has shown significant promise in optimizing yields, improving sustainability, and enabling data-driven decision-making in climate-resilient agriculture.

While comprehensive market sizing remains an evolving field, the widespread research interest and pilot programs reflect growing investment and scalability potential. Adoption trends indicate positive momentum, driven by policy support, youth engagement, and smart applications in precision agriculture, yet uneven due to socio-economic disparities. Thematically, the integration of AI into climate-smart agriculture emerges as pivotal for enhancing food security, promoting environmental stewardship, and aligning with global Sustainable Development Goals (SDGs), signaling a transformative pathway for the agricultural sector in the face of climate change.

Table 1: Key Thematic Insights on AI in Agriculture.

Theme	Key Findings	Sources (Year)
Adoption Barriers & Technological Impacts	- Limited awareness, digital literacy, and high costs are major barriers. to AI and IoT adoption, especially among smallholder farmers.	Ahmad et al. (2024), Bahari et al. (2024), Idris and Zulkifli (2024), Hassim et al. (2024)
	-Security, privacy, and ethical concerns hinder full IoT integration.	Ali et al. (2024a), Ali et al. (2024b), Hasan et al. (2024)
	- Infrastructure limitations (e.g., connectivity, power supply) slow tech deployment in rural areas.	Ardiansah et al. (2024), Baharin et al. (2024), Hanafi et al. (2024)
	-Integration of AI, IoT, blockchain, and computer vision improves precision, traceability, and sustainability.	Akbar et al. (2024), Huo et al. (2024), Hazwan Abd Manaf et al. (2024), Hasan et al. (2024)
Market Size & Growth	-Smart agriculture and climate-smart technologies are expected to expand significantly in Southeast Asia due to increasing climate risks.	Aziz et al. (2024), Afifah et al. (2024), Ajatasatru et al. (2024)
	-Government and private investments are catalyzing the growth of AgriTech markets in Asia.	Abubacker and Raheem (2024), Fauzi et al. (2024), Guilin et al. (2024)
	-The bioeconomy and Agri 4.0 push are positioning AI as a key growth driver in Malaysia.	Baharin et al. (2024), Hashim et al. (2024), Bahari et al. (2024)
Adoption Trends	-Younger generations and digitally literate farmers show higher acceptance of AI tools.	Hassan et al. (2024), Hanh et al. (2024), Azlan et al. (2024)
	-Mobile applications, IoT, and geospatial technologies are being adopted for urban and precision farming.	Che'Ya et al. (2024), Ismail and Ismunanto (2024), Jadhav et al. (2024)
	- Bibliometric and scientometric reviews show rising global research focus and publication trends in smart agriculture.	Al Junid et al. (2024), Bala and Kaur (2024), Azlan et al. (2024)
Thematic Insights	-Digital transformation in agriculture fosters sustainability, resource efficiency, and climate resilience.	Fauzi et al. (2024), Mohd Faizul Emizal Mohd and Astri Idayu (2024), Bazrafkan et al. (2023)
	- AI-powered irrigation, disease detection, and yield prediction significantly enhance productivity.	Jadhav et al. (2024), Hazwan Abd Manaf et al. (2024), Akbar et al. (2024), Ardiansah et al. (2024)
	-Policy support, education, and capacity-building programs are crucial for equitable AI adoption across farmer demographics.	Hassan et al. (2024), Idris and Zulkifli (2024), Hassim et al. (2024)
	- A circular economy and sustainable digital practices are core to smart agriculture in the context of climate change.	Baharin et al. (2024), Bazrafkan et al. (2023), Farhan et al. (2025)

4.7. National Agrofood Policy 2.0 (NAP 2.0)

The National Agrofood Policy 2.0 (NAP 2.0) reflects Malaysia's strategic direction to revitalize its agro-food sector post-COVID-19, with a strong emphasis on sustainability, resilience, and productivity. A central pillar of the transformation is the integration of digital technologies and AI, aiming to modernize agricultural practices and strengthen national food security.

4.7.1. Digitalization as a Core Strategy in NAP 2.0

NAP 2.0 aligns with Malaysia's broader digital economy aspirations, embedding AI, IoT, big data, and precision technologies into farming ecosystems (Bahari et al., 2024; Bala & Kaur, 2024). The policy specifically calls for the expansion of smart farming practices and digital agro-entrepreneurship, positioning digital transformation as essential for boosting productivity and addressing labor shortages.

NAP 2.0 also prioritizes capacity building and digital literacy among farmers. However, Ahmad et al. (2024) and Hassim et al. (2024) highlight that while the policy envisions a tech-driven agricultural future, adoption among smallholders remains low due to barriers in access, affordability, and awareness.

4.7.2. Role of AI in Smart and Sustainable Agriculture

AI plays a transformative role in real-time monitoring, disease detection, precision irrigation, and yield prediction (Akbar et al., 2024; Hazwan Abd Manaf et al., 2024). Under NAP 2.0, such capabilities support Climate-Smart Agriculture (CSA), which is critical in combating the effects of climate change (Afifah et al., 2024; Bazrafkan et al., 2023).

Moreover, digital twins, blockchain, and machine learning are emerging as core technologies ensuring traceability, trust, and transparency in the food supply chain (Ali et al., 2024b; Hasan et al., 2024), reinforcing food safety and sustainability goals.

4.7.3. Strengthening IoT and Data Infrastructure

The evolution of IoT in paddy cultivation, as studied by Al Junid et al. (2024), and data-driven irrigation systems (Ardiansah et al., 2024; Hanafi et al., 2024) mirrors NAP 2.0's commitment to technology-driven water management and resource efficiency. These innovations align with the policy's focus on resilient agriculture infrastructure.

The integration of mobile apps and geospatial tools into urban farming (Che'Ya et al., 2024) and IoT-based fertigation systems (Bariman et al., 2024) reflect the granular adoption of digital tools supported by the policy framework.

4.7.4. Human Capital and Behavioral Factors

Despite its ambitions, NAP 2.0 faces implementation hurdles. Studies (Aziz et al., 2024; Idris & Zulkifli, 2024) reveal that farmer readiness and willingness to embrace AI technologies are heavily influenced by perceived usefulness, digital competence, and trust in tech. Furthermore, gender and youth inclusion in the digital agricultural workforce remains a challenge that needs targeted policy intervention (Hassan et al., 2024).

4.7.5. Toward an Inclusive Digital Agro-ecosystem

Efforts to bridge the digital divide must consider socioeconomic inequalities. Digital transformation must be inclusive, ensuring that marginalized and small-scale farmers are not left behind (Hassim et al., 2024). Equally, cybersecurity and data privacy, as explored by Ali et al. (2024a), are critical issues under-addressed in current policy implementation strategies.

5. DISCUSSION AND CONCLUSION

The application of Artificial Intelligence technologies in agriculture holds transformative potential to address core challenges within the sector, including resource management, productivity constraints, and labor shortages. With the advancement of AI-driven technologies, smart agriculture has become an invaluable tool for enhancing the efficiency of resource usage, which is essential given the demands for sustainable food production (Nguyen et al., 2024). AI systems designed for crop monitoring and disease detection enable farmers to perform timely interventions, potentially improving crop yields and reducing losses. These systems integrate real-time data from sensors, weather models, and historical data to offer predictive insights that help farmers make informed decisions, which is critical for maintaining crop health and yield quality. Moreover, AI-enhanced supply chain solutions address another pressing challenge waste reduction. By optimizing inventory management, reducing spoilage through predictive analytics, and improving logistics efficiency, AI has the potential to reduce food waste significantly and bolster farmers' access to markets (Hassim et al., 2024). This can be especially beneficial for small-holder farmers, who often face barriers to market access. However, realizing these benefits requires overcoming several critical barriers, which include high implementation costs, inadequate digital infrastructure, and limited awareness among farmers of AI's potential value (Hassim et al., 2024). These barriers are pervasive in the Malaysian agricultural landscape and present a substantial impediment to the widespread adoption of AI. The Malaysian government has acknowledged the need for digital transformation in agriculture through policies such as the National Agrofood Policy 2.0. However, while the policy framework signals a proactive approach toward embracing smart agriculture, the success of such policies is contingent on effective stakeholder collaboration and comprehensive support systems (6Wresearch, 2024). Key initiatives, including subsidies for technology acquisition, training programs to build digital literacy among farmers, and infrastructure investments to support connectivity in rural areas, are essential components of creating an enabling environment for AI adoption in agriculture. Without such support, the digital divide between urban and rural areas may continue to hinder smallholder farmers, thereby limiting the equitable distribution of AI's benefits across the agricultural sector. The implications of the review extend beyond technological adoption and impact the broader goals of sustainable agriculture and food security in Malaysia. By implementing AI technologies effectively, Malaysia could improve the efficiency and resilience of its agricultural systems in the face of climate change and resource constraints. For instance, AI-driven solutions could play a role in addressing water scarcity and optimizing land use, helping mitigate some of the adverse impacts of climate change on agriculture. In addition, the scalability of AI technologies across various farming practices, from large plantations to smallholder farms, can foster inclusive growth within the sector, supporting both commercial and subsistence farmers (Nguyen et al., 2024).

Further, the review underscores the importance of integrating socio-economic factors into the AI adoption process. Smallholder farmers, who make up a large proportion of Malaysia's agricultural sector, may lack the financial resources or technical expertise to adopt AI without significant external support. Governmental policies should therefore prioritize equitable access to digital resources, ensuring that all farmers can benefit from AI-driven advancements. Moreover, building farmer awareness and digital literacy through targeted training and education programs will be crucial to address the knowledge gap in smart agriculture and maximize the potential of AI technologies. The review, while comprehensive in its scope, is subject to several limitations that highlight areas for future research. First, the literature examined largely focuses on specific case studies and regions within Malaysia, which may not fully represent the diversity of farming practices, socio-economic contexts, and environmental conditions across the country. As such, the findings may be more applicable to certain agricultural sectors, such as corn or palm oil, than others, thereby limiting the generalizability of the conclusions. Second, given the rapid pace of technological advancements, some of the technologies discussed may soon become outdated or be replaced by newer, more efficient solutions. Future reviews should incorporate continuous updates to account for such changes in the AI landscape. Based on the insights gained from the review, several avenues for future research emerge that could further advance understanding and support the development of AI technologies in Malaysian agriculture. First, there is a need for studies that examine the scalability of AI technologies across different types of agricultural operations, from smallholder farms to large agribusinesses. This would help identify the specific conditions and resources required for successful AI implementation at various scales, providing tailored recommendations to support diverse farming systems. Moreover, future research should focus on evaluating the socio-economic impacts of AI on rural communities and smallholder farmers. By investigating the potential for AI to create economic opportunities and increase income stability, researchers could provide valuable insights into how digital transformation can contribute to rural development and reduce income disparities within the agricultural sector. Additionally, such research should explore the role of AI in promoting inclusivity, particularly for women and marginalized groups who may face unique barriers to accessing digital resources and technology. The environmental implications of AI adoption are another critical area for future investigation. Given the importance of sustainable agriculture, future studies should evaluate the environmental trade-offs associated with AI, including its energy usage, carbon footprint, and potential for electronic waste generation. Research in the area could inform strategies to minimize these environmental impacts, aligning AI adoption with Malaysia's sustainability goals. Finally, as AI adoption in Malaysian agriculture progresses, it will be essential to investigate the impact of policy interventions and regulatory frameworks on technology uptake and farmer empowerment. Policies that address data privacy concerns, provide financial incentives, and promote cross-sector partnerships could play a pivotal role in accelerating AI integration. Comparative studies with other Southeast Asian countries could offer insights into best practices and policy innovations that support smart agriculture, fostering regional collaboration and knowledge sharing. In conclusion, the review highlights the transformative potential of AI technologies in Malaysian agriculture, offering a path to overcoming persistent challenges related to productivity, resource management, and labor shortages. The integration of smart agriculture, AI-driven crop monitoring, and supply chain optimization solutions can enhance agricultural efficiency and resilience, contributing to Malaysia's food security and sustainability goals. However, significant barriers to adoption remain, including high implementation costs, limited digital infrastructure, and a lack of digital literacy among farmers. Addressing these challenges requires a coordinated effort from government, industry, and academia to provide comprehensive support for AI adoption through policy incentives, infrastructure investments, and farmer training programs.

The references collectively illustrate the transformative role of technology in advancing smart agriculture, while simultaneously revealing synergies and disparities in addressing challenges related to sustainability, socio-economic equity, and scalability. A recurring theme is the significance of integrating technological frameworks into agricultural practices, as demonstrated by Abubacker and Raheem (2024) and Karimi and Ataei (2024), who emphasize ubiquitous computing and climate-smart agriculture, respectively. Their insights align with localized studies, such as Ahmad et al. (2024) and Hassan et al. (2024), which focus on barriers to technology adoption among smallholder farmers. Collectively, these works stress the importance of tailored approaches for enhancing technology uptake within specific demographic and geographic contexts. Similarly, IoT's application in agriculture features prominently, with Bahari et al. (2024) detailing its impact on paddy cultivation, Akbar et al. (2024) exploring its potential in smart greenhouses, and Hanafi et al. (2024) highlighting water management's sustainability benefits. These studies, complemented by Che'Ya et al.'s (2024) geospatial applications in urban farming, underscore the necessity for integrated, multidisciplinary frameworks that harness IoT's capabilities while addressing contextual needs. Ethical and security concerns represent another critical dimension, as explored by Ali et al. (2024b), who highlight vulnerabilities inherent in AI-driven agriculture, contrasting with Hasan et al. (2024), who advocate for blockchain as a mechanism to ensure trust and sustainability. The juxtaposition reveals a significant gap in aligning technological innovation with ethical safeguards, which is imperative for fostering stakeholder confidence. Additional gaps persist in socio-economic and environmental dimensions. Ahmad et al. (2024) and Hassim et al. (2024) underscore how inequities hinder smallholders' access to smart farming technologies, while Bala and Kaur (2024) and Bazrafkan et al. (2023) emphasize the absence of comprehensive frameworks to evaluate environmental impacts. Baharin et al. (2024) further point to the underutilization of circular economy principles, and Farhan et al. (2025) highlight inadequate policy support as a global governance gap, hampering the scalability and widespread adoption of these innovations. Bridging these gaps necessitates a multi-faceted strategy involving policymakers, technologists, and farming communities. First, developing inclusive frameworks that incorporate incentive-based models can encourage smallholder participation while addressing inequities. Capacity-building initiatives tailored to enhance technological literacy among farmers can further support the goal. Additionally, integrating blockchain and AI technologies with robust ethical safeguards, as proposed by Hasan et al. (2024), can address cybersecurity challenges, ensuring data integrity and fostering trust. Embedding sustainability metrics into IoT and AI-driven frameworks, as suggested by Hanafi et al. (2024) and Bahari et al. (2024), is crucial for aligning technological advancements with long-term ecological goals. To tackle governance issues, region-specific guidelines, coupled with scalable prototypes, can provide actionable blueprints to address socio-economic and environmental challenges. These measures can collectively propel smart agriculture toward a sustainable, equitable, and resilient future, ensuring that technological interventions serve diverse stakeholders effectively and responsibly.

5.1. Implications of the Study

The adoption of smart agriculture technologies powered by the Internet of Things (IoT), machine learning, and artificial intelligence (AI) holds significant implications for sustainable farming practices and agricultural development. The integration of these technologies has been shown to optimize resource use, such as water and energy, improving crop monitoring, and enhancing overall farm efficiency (Chong Peng et al., 2024).

For example, IoT-based systems, like those applied to efficient irrigation and crop monitoring, offer a promising pathway to ensuring food security in the face of climate change (Lavanya et al., 2024). Furthermore, the ongoing advancements in smart hydroponic systems and smart agriculture are set to revolutionize vertical farming methods, providing a more sustainable approach to agriculture in urban environments (Azmi et al., 2024; Nor et al., 2024).

The shift towards climate-smart and smart agriculture practices can also enhance the resilience of agricultural systems to environmental stressors, including droughts and soil degradation, which are crucial for achieving long-term sustainability (Ma & Rahut, 2024; Razak et al., 2024). By embracing these technologies, farmers can make data-driven decisions that reduce operational costs, improve yields, and contribute to the sustainability of agricultural practices across the globe.

5.2. Limitations

Despite the promising potential of IoT and AI in agriculture, several challenges hinder their widespread adoption. One major limitation is the high initial cost of implementing smart farming systems, including IoT devices, sensors, and AI-driven analytics tools (Mat Rosly et al., 2024). The barrier is particularly significant for smallholder farmers in developing countries, where access to capital is often limited (Sodhi & Jamwal, 2024).

Additionally, the complexity of these technologies requires farmers to acquire new skills, and the lack of proper training can impede successful implementation (Ting & Chan, 2024). Another limitation lies in the technological infrastructure required to support these systems. In rural areas, where internet connectivity and access to electricity may be unreliable, deploying IoT and AI systems could be challenging (Nurul Raudah Bariah & Norasmiha Mohd, 2024). Data privacy and security concerns also pose risks as sensitive information about farm operations is collected and transmitted via interconnected devices (Shaari et al., 2024).

5.3. Future Research Directions

5.3.1. Longitudinal Studies on Adoption and Impact

To address dynamic changes over time in AI adoption, effectiveness, and farmer behavior, future research should include long-term, multi-year studies focused on:

- Adoption Dynamics and Behavioral Shifts: As highlighted by Ahmad et al. (2024) and Aziz et al. (2024), farmer adoption of AI-based technologies is influenced by trust, affordability, and knowledge. Longitudinal studies can track these variables and their evolution across farming seasons and policy changes.
- Productivity and Environmental Outcomes: Hashim et al. (2024) and Bazrafkan et al. (2023) emphasize that smart farming technologies may improve rice productivity and reduce environmental footprints. Future research should measure crop yield, water usage, and carbon footprint over multiple seasons using AI-based precision agriculture tools.
- Youth and Gender Inclusion over Time: As noted by Hassan et al. (2024), youth resilience in adopting CSA can be nurtured. A long-term study could explore how educational interventions and digital literacy training influence youth and women's participation in smart farming over several years.

5.3.2. Region-Specific Pilot Projects

Given Malaysia's agro-ecological diversity and varying digital infrastructure, future research should prioritize context-sensitive pilot implementations to assess scalability and customization needs:

- Smart Paddy Cultivation in Flood-Prone Areas: Based on Al Junid et al. (2024) and Idris and Zulkifli (2024), pilot studies in Melaka, Kedah, and Kelantan can examine how IoT sensors and AI forecasting improve yield and reduce crop failure in high-risk zones.
- IoT-based Horticulture in Urban and Peri-Urban Zones: Che'Ya et al. (2024) and Ismail and Ismunanto (2024) suggest that urban farming can benefit from geo-spatial AI and mobile tech. Regional trials in Klang Valley or Johor Bahru can evaluate feasibility in dense urban settings.
- Pilot Bioeconomy Integration in Sabah and Sarawak: Baharin et al. (2024) promote the circular economy in farming. Regional case studies in East Malaysia can test AI-driven waste-to-resource models, combining big data analytics and IoT monitoring in biodiversity-rich zones.

5.3.3. Cross-Country Comparative Pilots

Inspired by Ajatasatru et al. (2024) and Afifah et al. (2024), collaborative pilot projects between Malaysia, Indonesia, and India could assess regionally tailored CSA models supported by AI. Comparative pilots may include mango farming, tomato greenhouse management, or water-efficient irrigation practices, allowing for broader policy learning and technology standardization.

5.3.4. AI Ethics and Cybersecurity Impact Studies

Given the concerns raised by Ali et al. (2024a) and Ali et al. (2024b) regarding cybersecurity and ethical issues, longitudinal risk assessment frameworks should be developed and piloted across different regions and farming scales to ensure responsible AI integration in agriculture.

6. CONCLUSION

The analysis of the National Agrofood Policy 2.0 (NAP 2.0), viewed through the lens of recent scholarly contributions, reveals a policy framework that is both ambitious and progressive. It outlines a transformative blueprint aimed at positioning Malaysia as a digitally empowered and climate-resilient agrofood nation. While the strategic direction laid out by NAP 2.0 is clear and commendable, the realization of its goals depends heavily on the success of a multidimensional implementation approach. Key pillars such as infrastructure development, digital inclusion, capacity building through education, trust in digital systems, and robust regulatory frameworks must be collectively strengthened to support the transformation.

The review contributes meaningfully to the existing literature by integrating multidisciplinary perspectives from agronomy, digital technology, public policy, and socioeconomics. By doing so, it offers a holistic evaluation of the potential of artificial intelligence (AI) in revolutionizing Malaysia's agriculture sector. The study also identifies and emphasizes critical empirical and practical gaps, particularly in understanding adoption behaviors, ensuring data governance, and promoting equitable access to digital technologies. These gaps must be addressed to facilitate inclusive and sustainable innovation across the agrofood ecosystem.

Furthermore, the integration of AI within the frameworks of post-pandemic economic recovery and climate change adaptation is underscored as a central theme aligned with NAP 2.0 priorities. The review bridges theoretical policy aspirations with grounded technological applications, showcasing real-world case studies such as the use of hyperspectral imaging in rice farming and blockchain for food traceability. These examples illuminate the practical pathways through which AI can contribute to achieving food security, traceability, and sustainability.

Ultimately, the study enriches the academic and policy discourse by capturing emerging innovations and the evolving behavioral dynamics shaping Malaysia's agro-digital transformation. It reinforces the call for cross-sectoral collaboration, participatory governance, and adaptive regulatory mechanisms. Only through such coordinated efforts can AI and digital tools become effective enablers of a sustainable, resilient, and productive agricultural future in Malaysia's rapidly changing climatic and socio-economic landscape.

6.1. Declarations

6.1.1. Ethics Approval and Consent to Participate

Not applicable

6.1.2. Consent for Publication

Not applicable

6.1.3. Availability of Data and Materials

The study is a narrative review and does not involve the collection or analysis of original data from participants. All information and insights presented in the study are derived from existing literature, publicly available sources, and secondary data obtained from previous research. As such, no new datasets were generated or analyzed during the study.

6.1.4. Competing Interests

I, as the sole author of the article, declared that I have no competing financial or personal interests that could have influenced the work reported. The review article was conducted independently, with no external influences, funding, or affiliations that could have impacted the findings or interpretations presented.

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Author's contributions

The sole author has made substantial contributions to the conception, study, and writing of the review article. The author reviewed, edited, and approved the final manuscript, ensuring it met academic standards and provided a balanced, evidence-based discussion. The author confirms that the article represents original work and bears full accountability for the content presented in the publication.

AI-Assisted Language Review

The document has undergone language editing and grammar refinement using AI-based tools. The assistance provided was limited to checking sentence structure, grammar, and clarity to enhance the overall readability of the content. No changes were made to the originality, interpretation, or academic integrity of the work.

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APPENDIX A

Thematic Citation Map

Thematic	Focus	Citation
1. Climate-Smart Agriculture & Sustainability	Technologies, policies, and adoption factors aligned with sustainable and climate-resilient agriculture.	Afifah et al. (2024) Kumar and Aishwarya (2024) Ajatasatru et al. (2024) Aziz et al. (2024) Bazrafkan et al. (2023) Fauzi et al. (2024) Hassan et al. (2024) Hashim et al. (2024) Hassim et al. (2024)
2. Internet of Things (IoT) in Agriculture	IoT-based smart systems, smart agriculture, irrigation, fertigation, and infrastructure in agriculture.	Al Junid et al. (2024) Ardiansah et al. (2024) Bahari et al. (2024) Baharin et al. (2024) Bariman et al. (2024) Che'Ya et al. (2024) Mohd Faizul Emizal Mohd and Astri Idayu (2024) Hanafi et al. (2024) Hassim et al. (2024) Huo et al. (2024) Idris and Zulkifli (2024) Ismail and Ismunanto (2024) Jadhav et al. (2024) Alsayaydeh et al. (2024)
3. Artificial Intelligence (AI) & Computer Vision in Smart Farming	Deep learning, AI applications in detection, automation, and data analytics for farm productivity.	Akbar et al. (2024) Hazwan Abd Manaf et al. (2024) Huo et al. (2024) Ali et al. (2024b) Ali et al. (2024a)
4. Farmer Behavior, Adoption Barriers & Socioeconomic Insights	Farmer readiness, smallholder challenges, youth involvement, digital transformation readiness.	Ahmad et al. (2024) Hassan et al. (2024) Hassim et al. (2024) Aziz et al. (2024) Idris and Zulkifli (2024)
5. Blockchain, Cybersecurity & Data Privacy in AgriTech	Ethical implications, cybersecurity frameworks, trusted AI, and data-driven agriculture.	Ali et al. (2024a) Hasan et al. (2024) Ali et al. (2024b)
6. Digital Tools, Mobile Apps, and ICT in Agriculture	Information and communication technology (ICT), digital platforms, and app-based solutions.	Bala and Kaur (2024) Che'Ya et al. (2024) Hanh et al. (2024) Farhan et al. (2025)
7. Reviews, Bibliometrics, and Systematic Studies	Systematic reviews, bibliometric analysis, scient metric studies of smart agriculture research.	Azlan et al. (2024) Bala and Kaur (2024) Al Junid et al. (2024)
8. Region-Specific/Case-Based Insights (Malaysia, Brunei, India, Asia)	Localized smart agriculture implementations, regional strategies, and national policies.	Abubacker and Raheem (2024) – Malaysia Ajatasatru et al. (2024) – India Hassan et al. (2024) – Brunei Guilin et al. (2024) – Asia Hassim et al. (2024) – Malaysia Idris and Zulkifli (2024) – Malaysia