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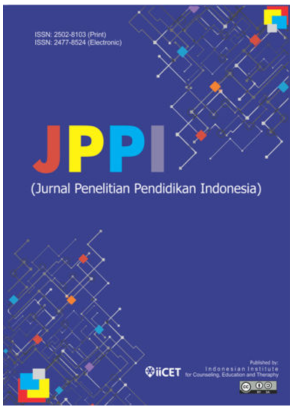

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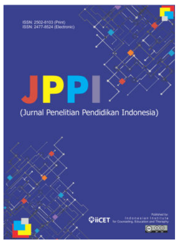

The utilization of digital technology and the internet of things (IoT) in the era of the industrial revolution 4.0

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ABSTRACT

The rapid advancement of digital technology and the Internet of Things (IoT) presents significant opportunities to enhance sustainable agricultural productivity. However, the integration of these technologies in agriculture faces challenges that remain insufficiently explored. This study aims to examine the role of digital technology and IoT in enhancing sustainable agricultural productivity, identifying both the benefits and challenges associated with their application. Using a qualitative literature review approach, the study analyzes peer-reviewed articles focusing on precision farming, soil sensors, and smart irrigation systems. Findings reveal that while digital technologies and IoT can substantially increase efficiency and productivity, barriers such as limited infrastructure, high implementation costs, and data privacy concerns hinder widespread adoption. The novelty of this study lies in its holistic approach, addressing not only the potential benefits but also the practical challenges of integrating these technologies into sustainable agriculture. The study provides significant insights for agricultural practitioners, policymakers, and technology developers, offering practical recommendations to overcome existing barriers and ensure the effective adoption of these innovations to drive sustainable agricultural development.

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Introduction

Sustainable agriculture faces significant challenges in the context of rapid global population growth and the escalating effects of climate change (Saleem et al., 2024). Digital technology and the Internet of Things (IoT) have shown great potential to enhance agricultural productivity in a more efficient and environmentally friendly manner (Dhanaraju et al., 2022). However, the adoption of these technologies in the agricultural sector faces barriers that are not yet fully understood, particularly in developing countries and regions with limited infrastructure (Manavalan & Jayakrishna, 2019). One of the main issues to address is how to integrate digital technology to optimize resource management, improve agricultural yields, and adapt to climate change (Getahun et al., 2024). According to data from the

Indonesian Ministry of Agriculture (2023), the agricultural sector in Indonesia continues to struggle with inefficient water usage and suboptimal land management, which contributes to a decline in agricultural output in several regions (Mufida, 2024).

This study aims to explore how the application of digital technology and IoT can enhance sustainable agricultural productivity, focusing on more efficient resource management and responsiveness to climate change (Koryati et al., 2023). The primary objective of this research is to identify the key benefits and challenges faced by farmers in adopting these technologies and to suggest solutions that can support broader adoption (Yokamo, 2020). In this study, sustainable agriculture is defined as the ability of agricultural systems to increase production without damaging the environment or compromising the welfare of farmers (Batra et al., 2025).

Although many previous studies have highlighted the potential of digital technology and IoT in agriculture, most have focused on one specific dimension or benefit, such as water use efficiency or crop health monitoring, without providing a holistic view of their integration in sustainable agriculture (Liu et al., 2020; Tao et al., 2021). One of the major gaps in the existing literature is the lack of attention to the practical challenges faced by smallholder farmers and the limited infrastructure in developing countries (Malik et al., 2022). This article contributes by providing a comprehensive analysis of digital technology and IoT applications in sustainable agriculture while exploring the barriers that must be overcome to ensure successful implementation.

The novelty of this article lies in its comprehensive approach to evaluating the application of digital technology and IoT in the agricultural sector, linking theory with practice, and providing context-specific recommendations that can be applied in developing countries (Rejeb et al., 2022). This study also differs from previous research by focusing on a critical analysis of the challenges in technology adoption and introducing a local perspective relevant to the issues faced by farmers in Indonesia. Thus, this research aims to fill the knowledge gap regarding the application of technology in sustainable agriculture in resource-limited regions.

The structure of this article begins with a literature review discussing the development of digital technologies and IoT in the context of sustainable agriculture. The study then delves into the methods used to collect data on the application of these technologies and subsequently discusses the findings and recommendations for more sustainable agricultural practices. The article concludes with a summary of the main contributions of the research and directions for future studies.

Method

This study employs a systematic literature review (SLR) approach, guided by the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) framework, to ensure a transparent, replicable, and rigorous process of literature collection and analysis (Lawal & Oguns-Obasohan, 2025). The objective of the review is to synthesize the existing body of knowledge on the application of digital technologies and the Internet of Things (IoT) in sustainable agriculture, with a particular focus on understanding their benefits, challenges, and the implications for developing countries (Neményi et al., 2022). A comprehensive search was conducted across multiple academic databases, including Scopus, Web of Science, and Google Scholar, which are known for their wide coverage of agricultural, technological, and interdisciplinary research (Moleong, 2000). The search was limited to studies published between 2010 and 2023, and included keywords such as "digital technology", "Internet of Things", "sustainable agriculture", "precision farming", "resource management", and "climate change adaptation to ensure relevance to the research topic (Dhanaraju et al., 2022; Manavalan & Jayakrishna, 2019).

From an initial pool of 50 articles, 35 studies were retained after applying predefined inclusion and exclusion criteria. The inclusion criteria required studies to focus specifically on the application of digital technologies or IoT in agriculture, particularly those that addressed sustainable agricultural practices and challenges related to climate change (Tao et al., 2021). Excluded were non-peer-reviewed sources, articles unrelated to IoT and digital technology in agriculture, and studies focusing on unsustainable agricultural practices (Rodriguez-Gallo et al., 2024). To ensure academic rigor, the quality of the selected sources was appraised using the CASP (Critical Appraisal Skills Programme) checklist, which evaluates the relevance, credibility, and methodological quality of the sources (Batra et al., 2025). This quality appraisal confirmed that the sources selected met high academic standards, ensuring the reliability of the study s conclusions.

Thematic analysis was used to synthesize and interpret the data from the selected studies . The analysis was conducted using a systematic coding process, starting with open coding to identify initial categories and emerging themes. Next, axial coding was applied to refine and group similar categories, followed by selective coding to establish core themes that emerged from the literature, which included efficiency in resource management, climate change adaptation, barriers to technology adoption, and stakeholder collaboration (Rejeb et al., 2022). Additionally, the analysis was validated through triangulation by cross-referencing studies from different regions and contexts. Expert consultations were conducted with three agricultural technology specialists to verify the accuracy and applicability of the interpretations. This expert validation process was critical in addressing local and regional nuances in technology adoption and ensuring the findings were relevant to real-world conditions (Malik et al., 2022). Furthermore, potential biases in the selection of literature were identified and mitigated. While the majority of studies highlighted positive impacts of IoT and digital technologies in agriculture, articles that reported on challenges, failures, or limitations of these technologies were also included to ensure a balanced view. This approach minimizes publication bias and ensures the findings are comprehensive and reflective of both successes and challenges (Liu et al., 2020). The review also incorporates a contextual reflection, particularly focusing on Indonesia as a case study for developing countries, where agriculture faces challenges such as inefficient water use, land degradation, and climate vulnerability. By focusing on this specific region, the study provides practical recommendations for policymakers, technology developers, and agricultural practitioners in similar contexts (Tzounis et al., 2017). This contextual approach enhances the practical relevance of the findings, offering insights tailored to the unique challenges of agricultural systems in developing countries.

Results and Discussions

Impact of IoT on Resource Management

The integration of the Internet of Things (IoT) in agriculture has significantly enhanced resource management, which is a cornerstone for achieving sustainable farming practices (Dhanaraju et al., 2022). IoT devices, such as soil moisture sensors and weather stations, provide real-time data that enables farmers to monitor environmental conditions accurately (Khanna & Kaur, 2019). This data-driven approach facilitates more precise irrigation practices, reducing water wastage and ensuring crops receive adequate hydration (Liu et al., 2020). For instance, studies show that smart irrigation systems can lead to water savings of up to 30% while maintaining optimal crop yields (Liu et al., 2020). However, while these benefits are well-documented in developed countries, their application in regions with limited infrastructure, such as rural parts of Southeast Asia and Africa, remains a significant challenge (Wójcicki et al., 2022). In these regions, unreliable internet and electricity supply often undermine the full potential of IoT systems.

Furthermore, IoT technologies also improve the efficiency of fertilizer and pesticide applications, which minimizes the environmental impact of overuse. By leveraging data analytics, farmers can target specific areas in need of treatment, reducing chemical input and promoting healthier crop growth (Tumiwa et al., 2022). The integration of IoT into resource management represents a key step toward sustainable agricultural practices, yet the adoption of these systems remains uneven. Economic barriers, such as the high initial costs of IoT devices and infrastructure, remain a major obstacle for smallholder farmers (Batra et al., 2025). Without subsidies or low-interest loans, widespread implementation is hindered, especially in developing countries where many farmers operate on narrow profit margins.

IoT's ability to foster collaboration among farmers and agronomists further enhances its impact. Data sharing platforms that integrate IoT data allow for better-informed decisions regarding crop rotation and soil health management (Nižetić et al., 2020). These collaborative platforms empower farmers to learn from one another′s experiences, which in turn boosts overall productivity and sustainability in the agricultural sector. However, the fragmented nature of rural agriculture in developing countries, coupled with limited access to technology, prevents full utilization of these platforms. Therefore, fostering collaborative networks must go hand-in-hand with addressing the infrastructural challenges faced by farmers in these areas.

Enhancing Crop Monitoring and Yield Prediction

The advent of IoT technologies has also revolutionized crop monitoring and yield prediction, providing critical tools for enhancing agricultural productivity. Precision agriculture techniques, which integrate satellite imagery and drone technology, allow for detailed monitoring of crop health and growth patterns (Hati & Singh, 2021). These technologies give farmers insights into plant health and stress levels, enabling timely interventions to prevent losses and optimize yields. However, while these systems have shown promise in certain regions, there is still a lack of comprehensive studies examining their cost-effectiveness in resource-constrained settings.

Yield prediction models that incorporate IoT data are becoming increasingly sophisticated. By analyzing historical yield data alongside current environmental conditions, farmers can predict crop yields with higher accuracy (S. Kumar et al., 2019). This predictive capability is crucial for farmers to plan ahead, allocate resources more efficiently, and meet market demands without overburdening the land or financial resources. However, discrepancies between different methodologies remain. Some studies rely on basic weather-based predictive models, while others incorporate machine learning algorithms to generate more precise forecasts (Paraforos & Griepentrog, 2021). A gap in the literature lies in the comparative analysis of these methodologies and the practical implications of adopting more complex predictive models in real-world agriculture (Sharma et al., 2022).

Machine learning algorithms, when integrated with IoT data, enhance the accuracy of yield predictions by factoring in variables such as soil moisture, temperature, and plant health (Tzounis et al., 2017). While the potential of these models is evident, their adoption has been slow due to the complexity of the algorithms and the need for significant computational power. Furthermore, the economic implications of these models have yet to be fully explored. For instance, while predictive models can provide actionable insights for farmers, the cost of implementing such technologies may outweigh the benefits for smallholder farmers, especially in regions where the return on investment is uncertain (Ayaz et al., 2019).

Challenges of Implementing Digital Technologies in Agriculture

Despite the significant benefits, the adoption of IoT technologies in agriculture faces several challenges that can hinder their widespread implementation (Ifty et al., 2023). One of the most prominent barriers is the lack of adequate technological infrastructure, particularly in rural areas of developing countries (Wójcicki et al., 2022). For IoT devices to operate effectively, reliable internet connectivity is essential; yet many rural areas still lack access to high-speed internet. The issue of inadequate power supply further complicates the situation, as IoT devices require a consistent energy source to function (Martos et al., 2021). The lack of infrastructure not only limits the effectiveness of IoT systems but also prevents farmers from accessing real-time data that could enhance their farming practices (Dhanaraju et al., 2022).

Another significant challenge is financial constraints. Smallholder farmers, especially those in developing countries, often face difficulties in financing the initial investment required for IoT technologies, including sensors and data analytics platforms (Batra et al., 2025). Without access to affordable financing options or government subsidies, many farmers cannot afford the upfront costs of implementing IoT systems (Stamborowski, 2023). This financial barrier perpetuates inequality in agricultural productivity, as larger, wealthier farms are able to invest in these technologies, while smaller farms remain underserved. The financial burden of IoT technologies is a critical issue that needs to be addressed through policy and financial support (Koryati et al., 2023).

Moreover, data privacy and security concerns are also significant challenges in the adoption of IoT in agriculture. As IoT systems generate vast amounts of data, issues related to data ownership, misuse, and breaches can undermine farmers' trust in these technologies (A. Kumar & Nayyar, 2019). Establishing clear data governance frameworks and ensuring robust security measures are essential for fostering trust among farmers and encouraging the adoption of IoT systems.

Future Directions for Sustainable Agriculture

Looking ahead, the future of sustainable agriculture lies in the continued integration of digital technologies and IoT (Day o lu & Turker, 2021). However, addressing the current challenges is essential to fully harness the potential of these technologies. One crucial direction is the development of affordable and accessible technologies tailored to smallholder farmers, particularly those in developing regions (Witkowski, 2017). Researchers and technology developers must prioritize creating low-cost IoT solutions that function effectively in diverse agricultural contexts, ensuring that all farmers benefit from these advancements.

Furthermore, the integration of artificial intelligence (AI) and machine learning (ML) with IoT data will be pivotal in enhancing decision-making processes and resource optimization in agriculture (Suneetha, 2023). These technologies can help create adaptive systems that respond dynamically to changing environmental conditions, improving resilience in agricultural production (Walter et al., 2017). By integrating AI with IoT, farmers can receive actionable insights for better irrigation schedules, pest control, and crop management.

Collaboration among farmers, technology providers, and policymakers will be crucial for overcoming the barriers to IoT adoption. Establishing data-sharing platforms and fostering knowledge exchange will help promote the adoption of best practices and innovative solutions (Ronaghi & Forouharfar, 2020). Additionally, as climate change continues to affect agricultural productivity, climate-smart technologies supported by IoT will play a critical role in helping farmers adapt to changing conditions. Real-time data on climate factors, such as temperature, rainfall, and soil health, will enable farmers to make informed decisions on planting schedules and crop selection (Symeonaki et al., 2021).

Conclusions

This review aimed to investigate the role of digital technologies and the Internet of Things (IoT) in enhancing sustainable agricultural productivity. The integration of IoT technologies has proven to be a transformative force in agriculture by enabling real-time data collection and analysis, facilitating precision farming practices, and optimizing resource use. Our review highlights that IoT applications, such as soil moisture sensors, smart irrigation systems, and data analytics platforms, significantly improve water management, reduce chemical inputs, and contribute to higher crop resilience and productivity. These technologies have shown the potential to revolutionize agricultural practices, especially by increasing resource efficiency and improving crop monitoring, which aligns with the research question regarding the potential of IoT to enhance agricultural sustainability.

However, the successful integration and widespread adoption of these technologies face several challenges, particularly for smallholder farmers in developing countries. The review identified key barriers, including infrastructure limitations, financial constraints, data privacy concerns, and knowledge gaps, all of which impede the full potential of IoT systems. These challenges emphasize the importance of addressing both technical and socio-economic issues to foster a more inclusive digital agricultural ecosystem. Consequently, future strategies must focus on developing affordable technologies, enhancing access to training and education, and encouraging collaboration among stakeholders to create a supportive environment for digital agriculture. These findings directly respond to the objective of understanding the practical implications of IoT adoption in agriculture, particularly in resource-constrained settings.

Looking ahead, further research is needed to assess the long-term impacts of IoT on agricultural sustainability. This includes evaluating the effectiveness of different IoT applications in diverse agricultural contexts, especially in regions with limited access to technology. It is also critical to explore the economic viability of these technologies for smallholder farmers and assess how policy frameworks can promote their adoption and integration into farming practices. This review suggests that fostering collaborative networks and developing inclusive policy frameworks will be crucial for overcoming the barriers to IoT adoption and achieving sustainable agricultural productivity. By focusing on these areas, researchers can generate valuable insights that guide the future of sustainable agriculture, ensuring that the benefits of digital technologies are accessible to all farmers, regardless of their socio-economic background.

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