JOURNAL PARAK
Plant and Agribusiness Research of
Applied Knowledge

Integrating Eco-Friendly Technologies into Crop Production Systems for Agricultural Sustainability: A Literature Review

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Article Information
Received: April 28, 2026
Revised: May 20, 2026
Online: June 02, 2026

Keywords
Sustainable Agriculture, Environmentally Friendly Technology, Precision Agriculture

ABSTRACT
Environmental degradation and the increasing demand for food production have become major challenges in modern agricultural systems, emphasizing the need for sustainable and environmentally friendly cultivation practices. This study analyzes the integration of environmentally friendly technologies in crop cultivation systems to support agricultural sustainability using a systematic literature review approach. A total of 15 scientific articles published between 2011 and 2025 were selected based on predefined inclusion criteria. The results show that technologies such as precision agriculture, Internet of Things (IoT), artificial intelligence (AI), and smart farming systems play a significant role in improving productivity, optimizing resource use, and reducing environmental impacts. These technologies enable real-time monitoring, data collection, and data-driven decision-making, leading to more efficient and adaptive agricultural practices. The findings further indicate that the integration of multiple technologies is more effective than single-technology applications, particularly in enhancing system performance through coordinated data processing and precision-based management. Despite these advantages, several challenges remain, including high implementation costs, limited technical capacity, and inadequate infrastructure. Therefore, the adoption of integrated environmentally friendly technologies requires strong policy support, investment in digital infrastructure, and capacity-building programs. Overall, technological integration represents a key strategy for achieving sustainable and resilient agricultural systems. These findings emphasize that integrating environmentally friendly technologies is a key strategy for achieving sustainable and resilient agricultural systems.

INTRODUCTION

The increasing global demand for food production and the growing awareness of environmental degradation have placed significant pressure on modern agricultural systems. Ensuring food security while maintaining environmental sustainability has become a critical challenge that requires more efficient and environmentally friendly farming approaches (Lee et al., 2021). Conventional agricultural practices, which often rely on intensive chemical inputs and extensive land use, have been associated with soil degradation, water pollution, and loss of biodiversity, making them less sustainable in the long term (Idier et al., 2024). Therefore, there is a growing need to shift toward more sustainable cultivation systems that integrate environmentally friendly technologies to balance productivity and ecological preservation (Padhiary et al., 2025).

In response to these challenges, environmentally friendly technologies have emerged as an important solution in transforming crop cultivation systems into more sustainable practices. Technologies such as precision agriculture, smart farming systems, Internet of Things (IoT), and artificial intelligence (AI) enable farmers to optimize input use and improve farming efficiency through data-driven decision-making (Padhiary et al., 2025). These technologies support site-specific crop management, which reduces unnecessary use of fertilizers, water, and pesticides while maintaining or even increasing productivity levels (Raj & Prahadeeswaran, 2025). As a result, the integration of digital and environmentally friendly technologies is increasingly recognized as a key strategy for achieving sustainable agricultural development (Singh, 2024). However, despite their potential benefits, the adoption of these technologies is often accompanied by significant trade-offs. High initial investment costs, maintenance expenses, and technological complexity may limit their economic feasibility, particularly for smallholder farmers. In some cases, the cost of implementation may outweigh short-term benefits, creating uncertainty regarding their long-term economic sustainability.

Recent studies have shown that precision agriculture plays an important role in improving agricultural efficiency and environmental performance. The use of technologies such as remote sensing, geographic information systems (GIS), and global positioning systems (GPS) enables more accurate monitoring of soil conditions and crop growth (Sharma, 2023). This allows farmers to apply inputs more precisely, reducing waste and minimizing environmental damage (Singh, 2024). Furthermore, precision agriculture supports data-based decision-making that improves yield prediction and overall farm management efficiency (Padhiary et al., 2025).

In addition, smart farming systems based on Internet of Things (IoT) technology have gained increasing attention in modern agriculture. These systems utilize interconnected sensors and devices to collect real-time data on environmental conditions such as soil moisture, temperature, and humidity (Abu et al., 2022). The availability of real-time data enables farmers to respond quickly to environmental changes, improving productivity and resource efficiency (Raj & Prahadeeswaran, 2025). Moreover, IoT-based systems contribute to automation in agricultural processes, reducing labor dependency and operational inefficiencies (Padhiary et al., 2025).

Artificial intelligence (AI) also plays a crucial role in supporting environmentally friendly agricultural systems by enhancing predictive analysis and decision-making capabilities. AI technologies can process large datasets to identify patterns that are difficult to detect through conventional methods (Padhiary et al., 2025). For example, AI can be used to predict crop yields, detect plant diseases early, and optimize irrigation scheduling (Sharma, 2023). These capabilities contribute to more efficient resource management and support sustainable agricultural practices (Idier et al., 2024). Nevertheless, the accessibility of these technologies remains uneven across regions and farming communities. Smallholder farmers, particularly in developing countries, often face financial, technical, and infrastructural constraints that limit their ability to adopt advanced agricultural technologies. This inequality of access may further widen the gap between large-scale commercial farms and resource-limited farmers. Moreover, several studies have reported implementation failures due to inadequate training, lack of technical support, and poor integration with local farming practices. Technologies that are not adapted to specific agroecological conditions or socio-cultural contexts often result in suboptimal performance or complete abandonment.

Another critical issue is the presence of technological bias, where most innovations are developed based on conditions in developed countries, making them less suitable for developing regions. This bias can lead to mismatches between technological design and local needs, ultimately reducing their effectiveness and sustainability.

Despite the numerous benefits of integrating environmentally friendly technologies in agriculture, several challenges still hinder their widespread adoption. High implementation costs remain a major barrier, particularly for smallholder farmers in developing regions. In addition, limited digital literacy and lack of technical knowledge reduce the effectiveness of these technologies. Infrastructure limitations and inadequate institutional support further slow down the adoption process. Moreover, existing studies often focus on individual technologies rather than examining their integrated impact on sustainable agricultural systems, resulting in a fragmented understanding of their overall effectiveness (Idier et al., 2024). There is also limited discussion on socio-economic factors influencing technology adoption across different farming contexts (Lee et al., 2021).

Based on these research gaps, this study aims to systematically review the integration of environmentally friendly technologies in crop cultivation systems, with particular attention to their benefits, limitations, and contextual challenges in different agricultural settings. The main research question is: How does the integration of environmentally friendly technologies contribute to sustainable crop cultivation systems? The objectives of this study are to identify key green technologies, analyze their impact on productivity and environmental sustainability, and evaluate the challenges associated with their implementation. The novelty of this study lies in its integrative and critical approach, which not only synthesizes the benefits of multiple technologies but also highlights trade-offs, inequalities, and contextual limitations to provide a more comprehensive understanding of sustainable agricultural development for future research and policy implications.

METHODS

This study employed a systematic literature review (SLR) method to examine the integration of environmentally friendly technologies in crop cultivation systems. This approach is used to provide a structured and comprehensive synthesis of existing scientific evidence related to green agricultural technologies. The data sources were obtained from major international scientific databases, including Scopus, Web of Science, Google Scholar, PubMed, and IEEE Xplore. These databases were selected to ensure broad interdisciplinary coverage of agricultural, environmental, and technological studies. A total of 15 articles published between 2011 and 2025 were selected for analysis.

The subjects of this study consist of peer-reviewed journal articles focusing on environmentally friendly agricultural innovations, including precision agriculture, smart farming systems, Internet of Things (IoT), and artificial intelligence (AI). The data sources were obtained from reputable international scientific databases. The article selection process involved several stages, including identification, screening, eligibility assessment, and inclusion based on predefined criteria. The inclusion criteria include: (1) articles published between 2011 and 2025, (2) studies discussing environmentally friendly or sustainable agricultural technologies, and (3) research focusing on crop cultivation system, and (4) articles published peer-reviewed journals. Relevant literature was obtained from major academic databases such as Google Scholar, ScienceDirect, and other scholarly sources.

The research procedure follows a systematic review process consisting of four main stages: identification, screening, eligibility, and inclusion. In the identification stage, relevant articles were collected using keywords such as "environmentally friendly agriculture," "precision agriculture," "smart farming," "IoT in agriculture," and "sustainable crop production systems." The search strategy applied Boolean operators (AND, OR) across the selected databases to ensure comprehensive and relevant results. The screening stage involved removing duplicate studies and selecting articles based on title and abstract relevance. The eligibility stage included a full-text review to ensure that selected articles met all predefined criteria. Finally, the inclusion stage determined the final set of studies used for analysis.

After the screening and eligibility process, a total of 15 peer-reviewed journal articles that fully met the inclusion criteria (2020–2025, relevant scope, and full-text availability) were selected for final analysis. Older references (e.g., 2011, 2017, 2018) were retained only as supporting theoretical background in the Introduction and Discussion sections, but were not included in the core systematic review dataset. The selected articles were analyzed qualitatively by identifying key themes, technological approaches, benefits, and challenges related to sustainable agriculture.

The materials used in this study consist of secondary data obtained from scientific journals, review articles, and conference proceedings. No primary data collection involving humans or animals was conducted; therefore, ethical approval was not required. All data used in this study are publicly accessible through academic databases, ensuring transparency and replicability. Any limitations regarding data availability are acknowledged and will be addressed in future research development.

Data collection was conducted through a structured search strategy using academic databases (Scopus, Web of Science, Google Scholar, PubMed, and IEEE Xplore) and search engines. Keywords were combined using Boolean operators such as AND and OR to ensure comprehensive coverage of relevant literature. The selected articles were then organized systematically to support the review process. The extracted data include information on types of environmentally friendly technologies, implementation methods, productivity outcomes, resource efficiency, and environmental impacts. A standardized data extraction form was used to collect the following information from each study; type of environmentally friendly technology, implementation method, study location, productivity outcomes, resource efficiency indicators, and environmental impacts.

Data analysis was conducted using qualitative content analysis. The selected studies were categorized based on technological type, application area, and sustainability outcomes. The analysis process involved coding, classification, and thematic synthesis to identify patterns, relationships, and key findings across the literature. This method allows for a comprehensive understanding of how environmentally friendly technologies contribute to agricultural sustainability.

To ensure validity and reliability, this study applies a transparent and systematic review protocol with clearly defined inclusion and exclusion criteria. The structured methodology enhances consistency in data selection and analysis. In addition, the use of multiple sources helps reduce bias and improves the robustness of the findings. The study also follows a systematic review framework aligned with PRISMA guidelines to enhance transparency and reproducibility. The research design is also replicable, allowing future researchers to apply similar methods in related studies.

RESULTS

The findings from the 15 selected studies (2011–2025) indicate that the integration of environmentally friendly technologies is a key strategy in developing sustainable crop cultivation systems. Technologies such as precision agriculture, Internet of Things (IoT), artificial intelligence (AI), and smart farming systems are widely applied to improve agricultural practices. These technologies enable real-time monitoring, data collection, and analysis, leading to more accurate and data-driven decision-making. Artificial intelligence supports predictive analysis, including crop yield estimation, disease detection, and resource optimization, while IoT facilitates continuous field monitoring and system automation. Across the reviewed studies, the integration of multiple technologies demonstrates higher effectiveness compared to single-technology applications, particularly in improving efficiency, productivity, and environmental sustainability. Despite these benefits, several challenges remain, including high costs, system complexity, limited technical knowledge, and inadequate infrastructure. These findings emphasize the need for policy support, infrastructure development, and capacity-building programs to enhance the adoption of environmentally friendly technologies in agriculture.

1. **The Role of Precision Agriculture as an Environmentally Friendly Technology in Sustainable Crop Cultivation Systems**

Precision agriculture utilizes advanced technologies such as remote sensing, GPS, GIS, and digital mapping systems to support site-specific farm management. Through these tools, farmers are able to identify spatial variability in soil conditions, crop health, and nutrient distribution more accurately. As a result, agricultural inputs such as water, fertilizers, and pesticides can be applied in a more targeted and efficient manner. This reduces unnecessary input usage and minimizes environmental degradation. In addition, precision agriculture supports more sustainable land management practices by maintaining soil fertility and reducing chemical accumulation in agricultural ecosystems.

Furthermore, precision agriculture contributes significantly to improving resource efficiency in crop cultivation systems. The ability to monitor field conditions in real time allows farmers to make more precise decisions regarding irrigation and fertilization. This not only reduces production costs but also improves overall crop yield stability. By applying inputs only where they are needed, farmers can avoid overuse of chemicals that may harm soil and water quality. This efficiency is particularly important in addressing the challenges of climate variability and increasing production costs in agriculture. Therefore, precision agriculture plays a key role in promoting both economic and environmental sustainability in farming systems (Lee et al., 2021; Singh, 2024).

In addition, precision agriculture enhances crop monitoring and predictive analysis capabilities, which are essential for sustainable farming practices. Advanced sensing technologies enable continuous monitoring of crop growth stages, soil moisture levels, and nutrient conditions. This allows for early detection of potential agricultural problems such as pest infestations, nutrient deficiencies, and water stress. With this information, farmers can take timely corrective actions before significant crop losses occur. Consequently, productivity increases while resource waste is reduced.

Moreover, precision agriculture plays a crucial role in supporting environmentally friendly water management practices. Smart irrigation systems based on sensor data help optimize water use by delivering the right amount of water at the right time. This is particularly important in regions facing water scarcity and irregular rainfall patterns. By reducing both over-irrigation and under-irrigation, precision agriculture helps maintain crop health while conserving water resources. This contributes directly to long-term environmental sustainability and resilience in agricultural systems. The importance of efficient water use in sustainable farming is also emphasized by Padhiary et al. (2025).

Despite its benefits, the implementation of precision agriculture still faces several challenges, including high initial investment costs, limited digital infrastructure, and lack of technical expertise among farmers. In addition, limited access to digital infrastructure and technical knowledge reduces the effectiveness of these technologies in some regions. Farmers may also face difficulties in interpreting and utilizing complex data generated by precision systems. These challenges are more prominent in developing agricultural sectors where technological adoption is still limited. Therefore, addressing these constraints is essential to maximize the benefits of precision agriculture.

Overall, the findings indicate that precision agriculture plays a vital role in supporting environmentally friendly and sustainable crop cultivation systems. Its ability to optimize resource use, improve decision-making, and reduce environmental impacts makes it a key component of modern sustainable agriculture. However, successful implementation requires overcoming economic and technical barriers through training, policy support, and infrastructure development. Future improvements should focus on making precision agriculture more accessible and affordable for wider adoption across different farming contexts.

2. The Role of Smart Farming Systems Based on IoT and Artificial Intelligence in Supporting Environmentally Friendly Agriculture

Based on the selected studies, smart farming systems based on Internet of Things (IoT) and artificial intelligence (AI) are key environmentally friendly technologies in modern agriculture. These technologies enable real-time monitoring and data-driven management through sensors that collect environmental data such as soil moisture, temperature, and nutrient levels. This continuous monitoring improves farming efficiency and reduces unnecessary resource use. As a result, farming activities become more efficient and environmentally controlled. These systems contribute to reducing unnecessary resource use and supporting more sustainable agricultural practices (Abu et al., 2022; Raj & Prahadeeswaran, 2025).

Furthermore, the integration of IoT in agriculture improves operational efficiency by enabling real-time decision-making. Farmers can monitor crop conditions remotely and adjust irrigation, fertilization, and pest control strategies based on actual field data. This reduces dependency on manual observation and minimizes human error in farming operations. In addition, IoT-based systems help optimize input usage by ensuring that water and fertilizers are applied only when needed. This leads to better resource conservation and lower production costs. Therefore, IoT technology plays a significant role in supporting environmentally friendly and efficient crop cultivation systems.

Artificial intelligence enhances these systems by enabling predictive analysis such as crop yield estimation, disease detection, and resource optimization. AI models process large datasets to identify patterns and generate recommendations, improving decision-making accuracy. This allows farmers to anticipate potential risks and take preventive actions at an early stage. For example, AI-based systems can detect plant diseases before they spread widely, reducing the need for excessive pesticide use. This contributes to more environmentally friendly farming practices while maintaining productivity levels. The role of AI in enhancing agricultural decision-making has been highlighted by Sharma (2023).

Furthermore, the integration of IoT and AI supports automation in irrigation, fertilization, and pest control, leading to improved efficiency and reduced environmental impact. IoT provides real-time data input, while AI processes this information to generate actionable insights for farm management. This integration enhances the accuracy of agricultural decisions and improves overall productivity efficiency. It also supports automation in agricultural operations such as irrigation scheduling and fertilization management. As a result, farming systems become more adaptive, efficient, and environmentally sustainable; this integrated approach is increasingly recognized as a key innovation in modern agriculture.

Moreover, smart farming systems contribute significantly to environmental sustainability by reducing excessive use of natural resources. Efficient monitoring and automation help minimize water waste, fertilizer overuse, and chemical pollution in agricultural ecosystems. These improvements support soil health preservation and reduce negative environmental impacts associated with conventional farming methods. In addition, smart farming enhances the ability of agricultural systems to adapt to climate variability and environmental stress. This makes agriculture more resilient and sustainable in the long term and digital technologies in supporting green agriculture (Tilman et al., 2011; Pretty et al., 2018).

However, despite their advantages, the adoption of IoT and AI technologies in agriculture still faces several challenges. High implementation costs remain a major limitation, particularly for smallholder farmers in developing regions. Limited digital literacy and lack of technical skills also reduce the effectiveness of these technologies in practical use. In addition, inadequate internet connectivity and infrastructure constraints hinder the full operation of smart farming systems. These barriers limit the widespread adoption of digital agricultural technologies. Therefore, supportive policies, infrastructure development, and farmer training are essential to overcome these challenges (Carolan, 2020).

The findings consistently show that these technologies contribute to improved resource efficiency, reduced chemical usage, and enhanced sustainability outcomes across different agricultural contexts. Overall, IoT and AI-based smart farming systems play a crucial role in modern sustainable agriculture. Their ability to improve efficiency, enhance decision-making, and reduce environmental impacts makes them essential components of modern agricultural innovation. However, addressing economic, technical, and infrastructural barriers is necessary to ensure broader adoption. Future efforts should focus on increasing accessibility, affordability, and digital capacity among farmers to maximize the benefits of these technologies.

3. The Integration of Environmentally Friendly Technologies in Sustainable Crop Cultivation Systems

The findings from the selected studies indicate that the integration of environmentally friendly technologies is a key strategy in sustainable crop cultivation systems. Technologies such as precision agriculture, IoT, and artificial intelligence are increasingly combined to create more efficient and adaptive agricultural systems. This integration allows data collection, processing, and application to be conducted in a coordinated manner, improving decision-making accuracy. As a result, farmers are able to obtain more comprehensive information about field conditions and make better-informed decisions. This leads to improved efficiency in crop management and more sustainable agricultural practices.

Furthermore, integrated environmentally friendly technologies significantly enhance resource optimization in crop cultivation systems. Data collected from IoT sensors can be analyzed using AI-based systems and applied through precision agriculture techniques to determine the exact needs of crops. This coordinated system helps ensure that water, fertilizers, and pesticides are used more efficiently and only when necessary. Integrated systems improve resource optimization by ensuring that inputs such as water, fertilizers, and pesticides are used efficiently and only when needed. This reduces environmental pollution and production costs while maintaining productivity. This synergy between technologies supports both productivity improvement and environmental conservation. These findings align with previous studies emphasizing the importance of digital integration in sustainable agriculture (Talavera et al., 2017; Liakos et al., 2018).

In addition, integration enhances predictive capabilities, enabling farmers to anticipate risks such as climate variability and crop diseases. This contributes to more resilient agricultural systems. Real-time data from smart farming systems can be processed through AI algorithms to generate predictive insights, such as crop yield estimation and early warning of plant diseases. These insights can then be implemented using precision agriculture tools to optimize field-level interventions. This integrated decision-making system reduces uncertainty in farming operations and enhances productivity stability. Moreover, it allows farmers to respond more quickly to environmental changes and agricultural risks. Therefore, technology integration plays an important role in strengthening adaptive and resilient farming systems (Sharma, 2023). Across the reviewed studies, integrated technological approaches show the highest effectiveness in achieving sustainability outcomes, particularly when multiple technologies are applied simultaneously.

Moreover, the integration of environmentally friendly technologies contributes significantly to sustainable intensification in agriculture. This concept focuses on increasing agricultural output without expanding agricultural land or causing environmental degradation. Through integrated systems, farmers can achieve higher productivity while maintaining ecological balance and reducing pressure on natural resources. Soil quality, water availability, and biodiversity are better preserved through more efficient farming practices. In addition, integrated technologies support long-term food security by improving the sustainability of production systems. These benefits highlight the importance of a holistic technological approach in agriculture.

However, the implementation of integrated environmentally friendly technologies still faces several challenges. One of the main issues is the complexity of combining different technological systems that may not always be compatible with each other. High investment costs for integrated infrastructure also limit adoption, especially among small-scale farmers. In addition, the lack of technical expertise and digital skills makes it difficult for farmers to fully utilize integrated systems. Infrastructure limitations, such as poor internet connectivity, further hinder the effectiveness of technology integration in rural agricultural areas. These challenges reduce the potential benefits of integrated agricultural technologies (Carolan, 2020).

Furthermore, institutional and policy support plays a critical role in enabling successful technology integration in agriculture. Government policies that support digital transformation in the agricultural sector can accelerate the adoption of environmentally friendly technologies. Investments in digital infrastructure, training programs, and extension services are also essential to improve farmers' capabilities. Collaboration between researchers, policymakers, and industry stakeholders is needed to ensure effective implementation of integrated systems. Without adequate support, the adoption of advanced agricultural technologies will remain limited. Institutional and policy support are essential to accelerate adoption, including investment in digital infrastructure, farmer training, and collaborative innovation systems.

Overall, the integration of environmentally friendly technologies provides a comprehensive approach to achieving sustainable agricultural systems. By combining multiple digital and biological innovations, agricultural systems can achieve higher productivity, improved efficiency, and reduced environmental impact simultaneously. However, successful implementation depends on overcoming technical, economic, and institutional barriers. Future efforts should focus on improving system compatibility, increasing accessibility, and strengthening farmer capacity to ensure wider adoption of integrated sustainable agricultural technologies.

DISCUSSION

The findings of this study confirm that the integration of environmentally friendly technologies plays a crucial role in supporting sustainable crop cultivation systems by improving productivity, efficiency, and environmental performance. These findings are derived from the synthesis of selected studies, which consistently highlight the contribution of precision agriculture to resource optimization and yield improvement through site-specific management practices (Lee et al., 2021). The use of environmentally friendly technologies enables more efficient input allocation, reducing unnecessary use of water, fertilizers, and pesticides while maintaining crop productivity. This supports the argument that technological innovation is a key driver in achieving sustainable agricultural systems (Singh, 2024). Therefore, environmentally friendly technologies can be considered an essential component of modern sustainable agriculture (Padhiary et al., 2025). From a theoretical perspective, these results align with the concept of sustainable intensification, which emphasizes increasing agricultural productivity while minimizing environmental impacts. However, the degree of effectiveness varies depending on the type of technology and the context in which it is applied, suggesting that technological solutions alone may not fully address sustainability challenges.

In addition, the findings highlight that IoT and artificial intelligence significantly enhance the effectiveness of environmentally friendly agricultural systems. The ability of IoT to provide real-time environmental data supports more responsive and accurate farm management decisions (Abu et al., 2022). This is in line with previous research emphasizing the importance of real-time monitoring in improving agricultural efficiency and reducing environmental impacts (Raj & Prahadeeswaran, 2025). Furthermore, AI-based systems improve predictive capabilities, enabling early detection of crop diseases and more accurate yield forecasting (Liakos et al., 2018). This supports the hypothesis that digital technologies enhance decision-making processes in agriculture, leading to more sustainable outcomes (Kamilaris & Prenafeta-Boldú, 2018). While several studies report positive impacts of IoT and AI adoption, other studies indicate that the benefits are not always consistent across different farming systems. For example, some research suggests that the effectiveness of AI models depends heavily on data availability and quality, which may limit their applicability in data-scarce environments.

In contrast to studies that emphasize technological efficiency, other scholars argue that excessive reliance on digital technologies may increase system vulnerability, particularly in regions with unstable infrastructure. This indicates an ongoing debate in the literature regarding the balance between technological advancement and system resilience. The results also indicate that integrating multiple environmentally friendly technologies provides greater benefits compared to the use of individual technologies. The combination of precision agriculture, IoT, and AI creates a more comprehensive agricultural management system that improves coordination between data collection, analysis, and implementation (Wolfert et al., 2017). This finding extends previous studies that often examined agricultural technologies separately without considering their integrated effects (Idier et al., 2024). Integrated systems enable more accurate and efficient farm management, resulting in higher productivity and reduced environmental impact. This suggests that technology integration is essential for achieving long-term sustainability in agriculture (Klerkx et al., 2019).

However, the study also identifies several barriers that limit the adoption of environmentally friendly technologies in agriculture. High implementation costs remain a major challenge, particularly for smallholder farmers in developing countries (Rotz et al., 2019). This finding is consistent with previous research highlighting economic constraints as a key barrier to agricultural technology adoption (Carolan, 2020). In addition, limited digital literacy and lack of technical knowledge reduce farmers' ability to effectively utilize advanced technologies (Lee et al., 2021). Infrastructure limitations, such as inadequate internet connectivity, further hinder the implementation of smart farming systems (Klerkx et al., 2019). These barriers indicate that technological adoption is not solely determined by technical performance, but also by socio-economic and institutional factors. While some studies emphasize cost as the primary barrier, others highlight knowledge gaps and institutional weaknesses as more significant constraints, suggesting that adoption challenges are multidimensional rather than uniform.

From a broader perspective, the findings highlight the critical role of policy support and institutional involvement in promoting the adoption of green agricultural technologies. Government initiatives can facilitate access to technology, improve infrastructure, and provide financial support for farmers (Raj & Prahadeeswaran, 2025). In addition, training and capacity-building programs are necessary to enhance farmers' digital skills and technological awareness (Carolan, 2020). This is consistent with previous studies emphasizing the importance of institutional support in agricultural innovation processes (Padhiary et al., 2025). Furthermore, collaboration among stakeholders such as governments, researchers, and private sectors can accelerate the diffusion of environmentally friendly technologies in agriculture (Klerkx et al., 2019). Some studies argue that top-down policy approaches may not fully address local needs, emphasizing the importance of participatory and farmer-centered innovation systems. This suggests that policy design should consider local contexts to ensure successful technology adoption.

Finally, this study provides important implications for future research and agricultural practice. Future studies should further explore the combined impact of multiple environmentally friendly technologies in different agro-ecological contexts (Idier et al., 2024). There is also a need to investigate socio-economic factors influencing technology adoption in more detail, particularly in smallholder farming systems (Carolan, 2020). In addition, future research should address the existing gaps and contradictions in the literature, particularly regarding the trade-offs between technological efficiency, accessibility, and resilience. Strengthening policy frameworks and institutional support mechanisms is also essential to ensure wider adoption of sustainable agricultural technologies (Tilman et al., 2011). These directions will help enhance the effectiveness and inclusiveness of environmentally friendly agricultural systems.

CONCLUSIONS

The findings of this study demonstrate that the integration of environmentally friendly technologies; such as precision agriculture, IoT, and artificial intelligence (AI) plays a critical role in enhancing productivity, improving resource efficiency, and reducing environmental impacts in sustainable crop cultivation systems. The results indicate that integrated technological approaches provide greater effectiveness than single-technology applications, particularly through improved data-driven decision-making and system coordination. However, the adoption of these technologies remains constrained by economic, technical, and infrastructural barriers. Therefore, it is recommended that policymakers prioritize investment in digital infrastructure, develop targeted training programs to improve farmers' technological capacity, and promote collaborative innovation systems involving researchers, governments, and agricultural stakeholders. Future research should focus on evaluating the performance of integrated technologies across diverse agro-ecological contexts and developing more accessible and cost-effective solutions to support inclusive agricultural sustainability.

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