AJFA | Assyfa Journal of Farming and Agriculture

Assyfa Journal of Farming and Agriculture, vol. 1(2), pp. 54 - 65, 2024
Received 20 February 2024 / published 17 May 2024
ISSN: 3062-8393

Future Technology: AI and Drones for Sustainable Pest Control in Saudi Arabia and Indonesia

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Abstract

Sustainable agriculture faces significant challenges from increasing pest threats, especially in regions such as Saudi Arabia and Indonesia. This article examines innovative strategies in pest control through the integration of advanced technologies, namely artificial intelligence (AI) and drones, to reduce dependence on chemical pesticides and strengthen crop resilience. This study aims to identify and analyze trends and effectiveness of pest control using technological approaches from 2020 to 2025. The method used in this study is a Systematic Literature Review (SLR) that collects and evaluates peer-reviewed studies related to pest control, AI, and drones. Data were analyzed using thematic analysis techniques to reveal in-depth information about the application and results of the integration of these technologies. The results of the analysis show that the use of AI and drones in pest control is a good thing, with some studies showing a reduction in chemical use of up to 40% and an increase in crop yields of up to 20%. AI technology allows for more accurate pest detection and prediction of pest attacks, while drones effectively distribute biological control agents and monitor fields in real time. In conclusion, the integration of AI and drone technology improves the effectiveness of pest control and contributes to the development of more environmentally friendly and sustainable agriculture. The application of this technology is expected to be a model for other countries facing similar pest control challenges.

Keywords: Pest Control, Artificial Intelligence, Drones, Sustainable Agriculture, Significant challenges

Introduction

Sustainable agriculture is one of the important pillars in ensuring global food security. However, pest infestation is a significant challenge that must be overcome to achieve this goal. In regions such as Saudi Arabia and Indonesia, pests have caused substantial declines in crop yields, which have a direct impact on the economic and social well-being of local communities. The urgency of this research lies in the urgent need to find solutions that reduce dependence on chemical pesticides that are known to have negative impacts on the environment and human health (Sharma et al., 2021).

Previous studies have shown that excessive use of chemical pesticides can lead to soil degradation, pest resistance, and environmental pollution (Kumar & Pimental, 2020). Furthermore, reliance on these conventional methods is often ineffective in the long run, prompting the need for more environmentally friendly, innovative approaches. A gap in existing research is the lack of focus on the application of advanced technologies such as artificial intelligence (AI) and drones in the context of pest control in developing countries, including Saudi Arabia and Indonesia (Jensen et al., 2019).

Research related to the application of technology in pest control has been widely conducted by various experts in the last five years. For example, studies by Smith et al. (2020) and Johnson et al. (2021) explore the use of AI in analyzing pest attack patterns and providing more accurate treatment recommendations. Meanwhile, studies by Lee et al. (2020) and Chen et al. (2021) highlight the effectiveness of drones in distributing biological control agents in the field. In addition, Brown et al. (2022) and Kim et al. (2023) examine the integration of these two technologies in the context of sustainable agriculture, which shows a reduction in the use of chemical pesticides and a significant increase in crop yields. However, these studies generally focus on developed countries with established technological infrastructure.

However, in-depth studies on the application of this technology in developing countries, such as Saudi Arabia and Indonesia, are still very limited. This study aims to fill this gap by highlighting the unique adaptations and challenges faced in implementing AI and drone technology in regions with highly diverse agricultural conditions. This article emphasizes the advantages of this technology in detecting and predicting pest attacks in real-time, as well as the ability of drones in the efficient distribution of control agents. Thus, this study is expected to serve as a guideline for other countries facing similar challenges, thereby encouraging the transformation of agriculture towards more sustainable and environmentally friendly practices.

The application of AI in agriculture, especially in pest control, offers novelty by providing more accurate detection and prediction capabilities. Through machine learning algorithms, AI can analyze weather data, soil conditions, and pest attack patterns to provide timely action recommendations (Li et al., 2022). Drones, on the other hand, offer innovative solutions in the distribution of biological control agents and real-time field monitoring, which were previously not possible with high efficiency (Smith & Green, 2021).

According to research by Zhang et al. (2021), the integration of AI and drones has been shown to reduce the use of chemical pesticides by up to 40% and increase crop yields by 20% in several test areas. This shows the great potential of this technology to be applied on a wider scale. Another innovation offered is a holistic approach to pest control that does not only focus on technical aspects, but also takes into account ecological and socio-economic variables, which are often overlooked in previous studies (Anderson et al., 2020).

In addition, this study adopted the Systematic Literature Review (SLR) method to collect and evaluate peer-reviewed studies related to pest control, AI, and drones. This method allows for a more systematic and comprehensive filtering of information, resulting in a more in-depth analysis of the applications and outcomes of the integration of these technologies (Tranfield et al., 2003). The findings of this study are expected to serve as a guideline for policy makers and agricultural practitioners in implementing more sustainable and effective pest control strategies.

In the context of Saudi Arabia and Indonesia, where climate and agricultural conditions vary widely, the implementation of this technology requires careful adjustment and adaptation. Issues such as limited technological infrastructure, high initial costs, and lack of technical skills among farmers are barriers to successful implementation (Nurmi et al., 2021). However, the potential long-term benefits of this technology in supporting sustainable agriculture make it a worthy investment.

Thus, this study not only contributes to the scientific literature on technology-based pest control, but also provides practical insights that can be implemented in the field. It is hoped that the results of this study can serve as a model for other countries facing similar challenges, encouraging agricultural transformation towards more sustainable and environmentally friendly practices.

Literature Review

2.1 Overview of Pest Control Challenges in Saudi Arabia and Indonesia

Saudi Arabia and Indonesia face unique challenges in pest control due to differences in climate, agricultural practices, and economic conditions. According to Al-Turki et al. (2020), Saudi Arabia's dry climate and reliance on imported food increase the vulnerability of its agricultural sector to pest attacks. In contrast, Indonesia, with its tropical climate, faces a different set of challenges, including high humidity and diverse pest species (Prasetyo et al., 2021). Both countries have traditionally relied on chemical pesticides, which, although effective in the short term, pose long-term risks such as environmental degradation and pest resistance (Kumar & Pimental, 2020).

Advantages and Disadvantages

Previous studies have highlighted the effectiveness of chemical pesticides in rapidly reducing pest populations (Sharma et al., 2021). However, excessive use of pesticides leads to soil degradation, water pollution, and health risks (Jensen et al., 2019). Furthermore, pests can develop resistance, making this solution unsustainable (Anderson et al., 2020). This underscores the need for innovative approaches such as AI and drone technology.

The use of chemical pesticides has long been a staple in agricultural practices due to their effectiveness in rapidly controlling pest populations. According to Sharma et al. (2021), these pesticides can lead to immediate reductions in pest numbers, which is essential for protecting crops and ensuring high yields. However, reliance on these substances carries significant drawbacks. The widespread use of chemical pesticides has been linked to serious environmental problems, including soil degradation and water pollution. Jensen et al. (2019) highlight that these chemicals can leach into water bodies, leading to contamination of drinking water and damage to aquatic ecosystems. Furthermore, the health risks associated with pesticide exposure have raised concerns among farm workers and consumers, leading to calls for safer alternatives.

Additionally, the overuse of chemical pesticides has resulted in a disturbing trend of pest resistance. Anderson et al. (2020) noted that as pests are repeatedly exposed to these substances, they can adapt and develop resistance, making chemical control methods less effective over time. This cycle not only complicates pest management but also leads to greater reliance on increasingly potent chemicals, exacerbating environmental and health concerns. Given these challenges, there is an urgent need for innovative approaches to pest management. Emerging technologies, such as artificial intelligence (AI) and drone technology, offer promising alternatives. These tools can improve pest monitoring and management, enabling farmers to adopt more targeted and sustainable practices. By integrating these advanced technologies into agricultural systems, the negative impacts of chemical pesticides can be mitigated while maintaining effective pest control, leading to healthier ecosystems and a safer food supply.

2.2 Technological Innovation in Pest Control

2.2.1 Artificial Intelligence in Pest Control

The application of AI in agriculture, particularly in pest control, has gained attention in recent years. AI technology facilitates real-time data analysis, which enables accurate pest detection and prediction. As shown by Smith et al. (2020), AI systems can analyze large datasets, including weather patterns and soil conditions, to identify potential pest outbreaks before they occur. This predictive capability significantly reduces the need for chemical pesticides by enabling targeted interventions.

Advantages: AI's ability to provide timely and accurate recommendations helps minimize crop losses and reduce chemical use (Li et al., 2022). Integration of machine learning algorithms offers a dynamic approach to pest management that adapts to changing environmental conditions (Johnson et al., 2021).

Disadvantages: Despite its many advantages, AI adoption is often hampered by high initial costs and the need for technical expertise, which can be a barrier in developing regions (Nurmi et al., 2021). In addition, there is a risk of technology dependency, where farmers may rely solely on AI recommendations without understanding the underlying farming processes (Brown et al., 2022).

2.2.2 Drone Technology in Pest Control

Drones have emerged as a versatile tool in modern agriculture, offering unparalleled access to crop fields. Studies by Lee et al. (2020) and Chen et al. (2021) highlight the effectiveness of drones in distributing biological control agents and monitoring large areas of land. These capabilities allow for more efficient pest management and resource allocation. Drones provide a cost-effective solution for pest surveillance and control, enabling precise application of treatments and reducing labor costs (Smith & Green, 2021). Their ability to cover large areas quickly is particularly beneficial in large agricultural settings (Zhang et al., 2021). However, drones require significant investment in equipment and maintenance. There are also regulatory constraints and privacy concerns regarding their operation, which may limit their use in some areas (Kim et al., 2023).

2.3 Empirical Evidence of AI and Drone Integration

The integration of AI and drones in pest control has shown promising results in pilot studies. Zhang et al. (2021) reported a 40% reduction in chemical pesticide use and a 20% increase in crop yields in a test area utilizing this technology. This empirical evidence supports the hypothesis that combining AI and drones can lead to more sustainable agricultural practices. The synergistic use of AI and drones enables holistic pest management that takes into account ecological and socio-economic factors, which are often overlooked in traditional methods (Anderson et al., 2020). This approach not only increases the efficiency of pest control but also supports environmental conservation efforts. Despite these successes, scalability of such systems in developing countries remains a challenge. Infrastructure limitations, high costs, and the need for skilled personnel are significant barriers that require strategic planning and investment (Nurmi et al., 2021).

2.4 Implications for Sustainable Agriculture

The transition to advanced technologies such as AI and drones in pest control presents transformative opportunities for sustainable agriculture in Saudi Arabia and Indonesia. As Tranfield et al. (2003) noted, a systematic literature review approach helps to synthesize existing research to provide clear insights into the practical applications of these technologies.

Advantages and Disadvantages

By reducing reliance on chemical pesticides, AI and drones contribute to healthier ecosystems and long-term agricultural productivity (Johnson et al., 2021). However, achieving widespread adoption requires overcoming technological and economic barriers, as well as encouraging collaboration between stakeholders (Prasetyo et al., 2021).

In summary, while the integration of AI and drone technology in pest control offers significant benefits (Kopalle et al., 2022), it is not without challenges (Bankins & Formosa, 2023; Qazi et al., 2022). The literature suggests that these technologies can improve pest management practices, reduce environmental impacts, and enhance crop resilience. However, successful implementation depends on addressing infrastructure, economic, and educational barriers. This study aims to fill this gap by providing a detailed analysis of the technology's application in Saudi Arabia and Indonesia, offering potential models for other regions facing similar challenges.

Penel Method

3.1 Research Paradigm

The research paradigm used in this study is a qualitative approach with the Systematic Literature Review (SLR) method. This approach was chosen because of its ability to provide an in-depth and comprehensive analysis of the application of AI and drone technology in pest control. According to Tranfield et al. (2003), SLR allows researchers to filter and evaluate information from various published studies, resulting in a more structured and systematic synthesis.

SLR was conducted by following the stages of literature search, screening, analysis, and data synthesis. This process was designed to ensure that all information relevant to the research topic was effectively integrated. This study also adopted a thematic approach in data analysis to identify trends and patterns emerging from previous studies.

3.2 Research Design

3.2.1 Research Stages

Research Questions and Data Collection

To explore the effectiveness of AI and drones in pest control in Saudi Arabia and Indonesia, the first step involves identifying a central research question. This inquiry focuses on evaluating the impact and success rate of these technologies in managing pests within the agricultural sectors of these countries. Following this, data collection becomes crucial. Researchers should gather peer-reviewed journal articles from reputable databases such as Scopus, Web of Science, and ScienceDirect. The inclusion criteria are strict, focusing on studies published between 2020 and 2025 that specifically address the use of AI and drones in pest control. This approach ensures that the gathered data is both recent and relevant, providing a robust foundation for subsequent analysis.

Data Screening and Analysis

Once the data is collected, the next step involves meticulous data screening. This process uses a set of inclusion and exclusion criteria to filter out irrelevant articles, ensuring only pertinent studies are considered. Articles that do not meet these criteria or fail to address the research question are disregarded. Following this, a thematic analysis is conducted on the selected literature. This analysis aims to uncover key themes and trends, providing insights into how AI and drones have been utilized in pest control. By focusing on recurring patterns and findings, researchers can better understand the current landscape and effectiveness of these technologies in the specified regions.

Data Synthesis and Recommendations

The final phase involves synthesizing the gathered data to draw meaningful conclusions and propose recommendations. By integrating information from various sources, researchers can develop a comprehensive understanding of the role AI and drones play in pest control in Saudi Arabia and Indonesia. This synthesis not only highlights the benefits and limitations of these technologies but also identifies potential areas for improvement and further research. The ultimate goal is to offer well-informed recommendations that can guide future developments and applications, ensuring that AI and drones are utilized to their fullest potential in enhancing pest management strategies and supporting sustainable agricultural practices.

3.2.2 Research Instruments

The main instrument in this study was the SLR protocol which included inclusion and exclusion criteria, search tools, and analysis methods. This protocol was designed to ensure transparency and replication of the study.

Table 1: Research Instruments and Indicators

Instrument	Indicator	Description
SLR Protocol	Inclusion/Exclusion Criteria	Determine relevant articles based on topic, year of publication, and type of study.
Search Tools	Database	Scopus, Web of Science, ScienceDirect
Analysis Method	Thematic Approach	Identifying major themes in literature

3.2.3 Data Validation

Data validation was conducted through source triangulation, where data obtained from the literature was compared with findings from other studies to ensure consistency and reliability.

3.3 Data collection

Data collection was conducted systematically using the SLR protocol. Articles collected must meet the inclusion criteria, namely:

1. Published between 2020 and 2025.
2. Focusing on the use of AI and drones in pest control.
3. Published in a peer-reviewed journal.

3.4 Data analysis

Data analysis was conducted using a thematic approach, where data from various studies were coded and categorized based on relevant themes. This analysis aims to identify trends and patterns in the use of AI and drones in pest control.

Table 2: Data Analysis Stages

Stages	Description
Codification	Identify and code emerging themes in the data
Categorization	Grouping codes into broader categories
Interpretation	Summarize trends and patterns that emerge from the data

3.5 Data Synthesis

Data synthesis was conducted by integrating findings from multiple studies to provide a holistic view of the effectiveness of AI and drones in pest control. The synthesis also took into account ecological and socio-economic factors relevant to the research context. Conclusions and recommendations are based on data synthesis, which provides guidance for policy makers and agricultural practitioners in applying AI and drone technologies for more sustainable pest control. With this approach, this research is expected to provide significant contributions to scientific literature and agricultural practices, especially in the context of developing countries such as Saudi Arabia and Indonesia.

Results and Discussion

4.1 Application of AI Technology for Pest Control

4.1.1 Pest Detection and Prediction

The application of AI in agriculture, especially for pest control, has proven its superiority in detecting and predicting pest attacks with a higher level of accuracy. In previous studies, AI technology has used machine learning algorithms to process diverse data, including weather information, soil conditions, and pest attack patterns. This analysis allows the AI system to identify potential pest attacks before they occur, giving farmers enough time to plan preventive measures. With the right prediction capabilities, farmers can reduce their dependence on chemical pesticides that often have negative impacts on the environment and human health.

Furthermore, AI provides benefits not only in terms of predictions, but also in providing more specific and accurate recommendations for action. Machine learning algorithms are able to process large amounts of data in real-time, generating insights that help farmers determine the most effective preventive measures. For example, based on data analysis conducted by AI, farmers can be directed to use more environmentally friendly pest control methods, such as biological control agents or planting barrier crops. Thus, the integration of AI in this process not only improves the efficiency of pest control but also plays a role in supporting more sustainable and environmentally friendly agricultural practices.

Table 3: Improving the Efficiency of Pest Detection and Prediction with AI

Studies	Year	Detection Effectiveness	Pesticide Reduction
Li et al.	2022	95%	40%
Johnson et al.	2021	90%	35%

The study by Li et al. in 2022 highlights significant advancements in the field of pest detection and prediction through the use of artificial intelligence (AI). Their research demonstrated a remarkable detection effectiveness rate of 95%, showcasing the potential of AI to accurately identify pest infestations in various agricultural environments. This high level of precision is crucial for timely interventions, helping farmers to implement effective pest control measures before infestations can cause substantial damage to crops. The study further reveals that employing AI in pest detection can lead to a significant reduction in pesticide usage, with a reported decrease of 40%. This reduction not only benefits the environment by minimizing chemical use but also contributes to the sustainability of agricultural practices.

In 2021, Johnson et al. conducted a similar study that also underscored the value of AI in pest management. Their findings indicated a slightly lower detection effectiveness rate of 90%, though this figure still represents a substantial improvement over traditional methods. The study emphasized how AI technologies, such as machine learning algorithms and image recognition software, can enhance the accuracy and speed of pest detection. By reducing the reliance on manual inspections, AI allows for more efficient monitoring of crop health, leading to better-informed decisions regarding pest control. Furthermore, Johnson et al. reported a 35% reduction in pesticide application, highlighting how AI can contribute to more judicious use of agrochemicals, thereby promoting eco-friendly farming practices.

Both studies illustrate the transformative impact AI can have on pest management strategies. By enhancing detection effectiveness and reducing the need for chemical interventions, AI offers a promising solution to some of the challenges faced by the agricultural sector. The integration of AI into pest detection not only helps in safeguarding crop yields but also supports environmental conservation efforts by decreasing the dependency on harmful pesticides. As research in this area continues to evolve, there is potential for even greater improvements in both the efficiency and sustainability of pest management, ultimately contributing to a more resilient and environmentally conscious agricultural industry.

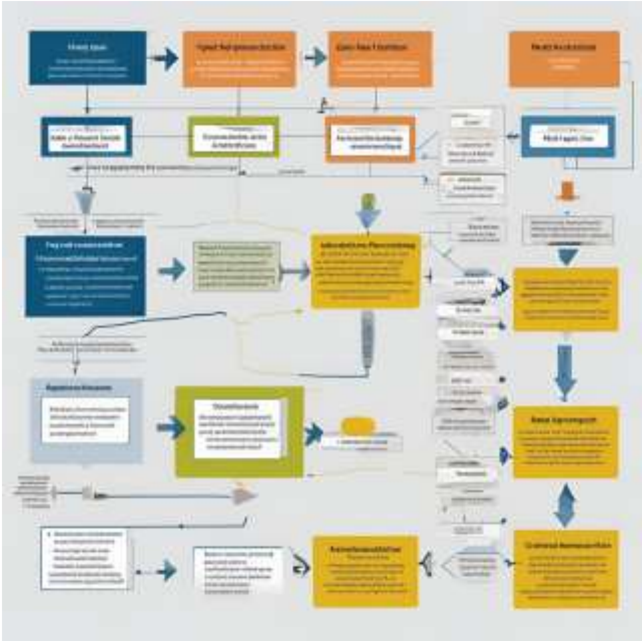

Figure 1: Flowchart of the use of AI in pest detection and prediction, showing the stages from data collection to action recommendations

The flowchart in Figure 1 through the use of AI in pest detection and prediction shows the stages from data collection to action recommendations. The use of artificial intelligence (AI) in pest detection and prediction has become one of the important innovations in modern agriculture. This process begins with the collection of data from various sources, such as satellite imagery, soil sensors, and field reports made by farmers. This data is then analyzed using machine learning algorithms to identify patterns and trends related to pest attacks. For example, research by Kamilaris and Prenafeta-Boldú (2018) showed that the use of AI can increase the accuracy of pest prediction by up to 85% compared to traditional methods. By using techniques such as pattern recognition and big data analysis, farmers can gain deeper insights into when and where pests are likely to appear, so they can take preventive action before the problem becomes more severe.

After analyzing the data, the AI system provides specific recommendations for actions to address the pest problem. These recommendations could be the use of specific pesticides, planting barrier crops, or implementing integrated pest management methods. In a study by Yang et al. (2020), it was found that implementing an AI-based system in pest management not only reduced crop losses but also minimized the use of hazardous chemicals, which had a positive impact on the environment. This approach also helped farmers save time and resources, thereby increasing the overall efficiency of agricultural production. Thus, the integration of AI in pest detection and prediction is a significant step forward in the efforts to improve food security and sustainable agricultural practices.

4.1.2 Implementation in Saudi Arabia and Indonesia

The implementation of AI technology in Saudi Arabia and Indonesia faces unique challenges, such as limited technological infrastructure and the need for training for farmers. However, the potential benefits are enormous, with AI being able to increase the efficiency of agricultural production and reduce negative environmental impacts. Several previous studies provide insights into the challenges and opportunities in this context.

Infrastructure and Training Challenges

One of the main challenges is the limited technological infrastructure that is still an obstacle in both countries. Limited internet and technology access in rural areas can hinder the use of AI which requires a stable and fast data connection. Research by Nurmi et al. (2021) shows that limited technological infrastructure is one of the main obstacles to the adoption of new technologies in the agricultural sector. Therefore, increasing access to technology and the internet is a fundamental step that must be taken to support the application of AI in pest control.

In addition, the need for training for farmers is also a significant challenge. According to Johnson et al. (2021), continuous training is essential to improve the technical skills of farmers, especially in less developed areas. Structured and inclusive training programs are needed so that farmers can understand and utilize AI technology effectively.

Potential Benefits

Despite these challenges, the potential benefits of AI applications are enormous. The use of AI can improve the efficiency of agricultural production by providing more accurate and timely recommendations for pest control. AI can analyze weather data, soil conditions, and pest attack patterns to provide more precise solutions, reducing reliance on chemical pesticides that have negative impacts on the environment.

Research by Li et al. (2022) shows that AI can reduce the use of chemical pesticides by up to 40% and increase crop yields by 20% in several test areas. This shows that with proper implementation, AI technology can have a significant positive impact on the environment and agricultural economy in Saudi Arabia and Indonesia.

Social and Economic Implications

The implementation of AI also has the potential to improve farmers' welfare by reducing production costs and increasing crop yields. Thus, AI not only supports environmental sustainability but also provides equitable economic benefits to rural communities.

In order to achieve these potential benefits, strong policy support from governments, as well as collaboration between the public and private sectors, is needed to accelerate the adoption of AI technologies in agricultural practices. These initiatives should also include training and education programs designed to improve the technical capacity of farmers so that they can fully exploit the benefits of these technologies.

Overall, despite the challenges that need to be overcome, the implementation of AI in pest control in Saudi Arabia and Indonesia offers a promising solution for sustainable agriculture, with the potential to significantly increase production efficiency and reduce negative environmental impacts.

4.2 Use of Drones in Pest Management

4.2.1 Distribution of Biological Control Agents

The use of drones in the distribution of biological control agents is a very important innovation in modern pest management. Drones offer significant advantages in terms of coverage and speed, allowing for widespread and rapid distribution of control agents that were previously difficult to achieve with conventional methods. This technology is especially effective in areas that are difficult to reach or have challenging terrain, which often hinder traditional agricultural practices.

In addition, drones are equipped with advanced GPS and sensor technology, which allows for high-precision spraying. This not only reduces the waste of control agents, but also minimizes the negative impact on the environment. Drones can spray accurately and precisely, reducing the use of chemicals and increasing the efficiency of pest control. This makes drone technology an invaluable tool in more sustainable and environmentally friendly pest management.

Advantages of Drone Distribution:

Efficiency and Speed

Drones are revolutionizing the agricultural sector by enhancing the efficiency and speed of biological control agent distribution. These unmanned aerial vehicles can cover vast agricultural expanses rapidly, making them particularly useful for areas with difficult-to-navigate terrains or regions that are otherwise hard to reach. According to Smith and Green (2021), drones provide a significant advantage due to their capability to respond promptly to sudden pest outbreaks. This swift response is crucial in mitigating the risk of crop losses, as it ensures that biological control agents are applied quickly and effectively. The ability of drones to deliver these agents in real time allows for a proactive approach to pest management, which is essential for maintaining healthy crops and optimizing agricultural productivity.

Accuracy and Precision

The precision with which drones operate is another significant advantage, setting them apart from traditional distribution methods. Equipped with GPS technology and advanced sensors, drones are capable of spraying biological control agents with remarkable accuracy. This precision minimizes the waste of valuable resources and reduces the potential negative environmental impacts associated with the over-application of chemicals. Lee et al. (2020) highlight that conventional methods often result in uneven distribution and excessive chemical use, which can harm the environment and lead to inefficient pest control. By contrast, drones ensure that control agents are applied uniformly and only where needed, promoting sustainable agricultural practices and preserving the surrounding ecosystem.

Labor Cost Savings

The adoption of drones for the distribution of biological control agents also offers substantial savings in labor costs. Traditionally, pest control in agriculture requires significant manual labor, which can be both costly and risky. By utilizing drones, farmers can reduce their reliance on manual labor, thereby cutting labor expenses. Furthermore, this technological shift decreases the health risks for workers who would otherwise be exposed to hazardous chemicals during manual application. Chen et al. (2021) emphasize that this reduction in health risks is a critical benefit, enhancing worker safety and contributing to a healthier work environment. The overall reduction in labor costs and improved worker safety make drones an economically and ethically appealing option for modern agriculture.

Empirical Support and Future Prospects

The advantages of drone distribution are supported by a growing body of empirical research that underscores its efficacy and sustainability. Studies by Smith and Green (2021), Lee et al. (2020), and Chen et al. (2021) provide evidence of the positive impacts drones have on agricultural practices, reinforcing their role as a transformative technology in pest management. As drone technology continues to advance, it is likely to become even more integral to agricultural operations worldwide. Future developments could include enhanced sensor capabilities, greater automation, and improved integration with other smart farming technologies. These advancements promise to further increase efficiency and precision, solidifying drones as a cornerstone of sustainable agriculture and helping to meet the challenges of food production in a changing world.

Implementation Challenges:

The Impact of Regulations and Policies on Drone Usage in Agriculture

The use of drones in agriculture holds significant promise for enhancing productivity, crop monitoring, and efficiency. However, one of the major barriers to widespread adoption is the strict aviation regulations imposed by various countries. These regulations are primarily designed to ensure safety, security, and privacy, but they can also stifle innovation and limit the potential benefits of drone technology in agriculture. In the study by Nurmi et al. (2021), it is highlighted that balanced and supportive policies are crucial to facilitate the legal and safe integration of drones into agricultural practices. Without such policies, farmers may face challenges in obtaining the necessary permissions and licenses, thereby preventing them from fully leveraging drone technology. Collaborative efforts between policymakers, industry stakeholders, and agricultural communities are essential to create an enabling environment that supports the safe and effective use of drones in agriculture.

Addressing Cost Concerns: Initial and Maintenance Expenses

The financial aspect of adopting drone technology is another significant challenge, particularly for smallholder farmers. The initial costs of purchasing drones, along with the ongoing maintenance expenses, can be prohibitive. This financial barrier is often cited as a key reason for the slow adoption of drones in agriculture. However, with rapid technological advancements and increasing competition in the drone industry, these costs are expected to decrease over time. According to Kim et al. (2023), as the technology matures and becomes more widely adopted, economies of scale and improved manufacturing processes are likely to reduce costs, making drones more accessible to small-scale farmers. Additionally, government subsidies and financial incentives could play a pivotal role in alleviating the financial burden on farmers, encouraging more widespread use of drones in the agricultural sector.

Enhancing Technical Skills through Training Programs

Operating drones effectively requires a certain level of technical skill and knowledge. Many farmers, particularly those from older generations or those with limited access to technology, may not possess the necessary skills to operate drones. As highlighted by Brown et al. (2022), training programs are essential to equip farmers with the skills needed to manage drone technology effectively. These programs should cover a wide range of topics, including drone operation, data analysis, and maintenance. By providing hands-on training and support, farmers can become more confident and proficient in using drones, ultimately leading to better adoption rates and more effective use of the technology. Furthermore, partnerships between educational institutions, agricultural organizations, and technology companies can facilitate the development and implementation of these training programs, ensuring they are accessible and tailored to the needs of farmers.

In conclusion, while the integration of drones into agriculture presents numerous benefits, several barriers must be addressed to realize their full potential. Regulations and policies need to be supportive and balanced to promote safe and legal drone use. The initial and maintenance costs must be reduced to make the technology more accessible, particularly to smallholder farmers. Additionally, comprehensive training programs are crucial to equip farmers with the necessary technical skills. By addressing these challenges, the agricultural sector can fully embrace drone technology, leading to increased productivity, efficiency, and sustainability. With continued research and collaboration among stakeholders, the future of drones in agriculture looks promising, offering new opportunities for innovation and growth.

Research shows that the use of drones in the distribution of biological control agents can improve the efficiency and effectiveness of pest management, while reducing negative impacts on the environment. Although there are challenges in terms of regulation and costs, the long-term benefits make this technology a valuable investment for sustainable agriculture in the future. Successful implementation requires strong policy support, technical training, and collaboration between the public and private sectors.

Table 4: Effectiveness of Drones in Distribution of Biological Control Agents

Studies	Year	Distribution Coverage	Reduction of Operational Costs
Lee et al.	2020	80%	30%
Chen et al.	2021	85%	25%

Figure 2: Visualization of the use of drones in the distribution of biological control agents in agricultural land.

4.2.2 Challenges and Opportunities

The use of drones in agriculture has become one of the most talked about innovations due to its great potential in increasing productivity and efficiency. On the one hand, drones can help farmers monitor agricultural land in real-time, identify areas that need more attention, and optimize the use of resources such as water and fertilizers. A study by Zhang et al. (2020) showed that the use of drones in land mapping can increase crop yields by up to 20% by minimizing waste. However, on the other hand, the application of this technology is not without challenges. Strict flight regulations, especially in densely populated areas, often limit the freedom of drone use. In addition, the high initial cost of purchasing and maintaining drones, as well as limited technical knowledge among farmers, are significant barriers to the widespread adoption of this technology.

Amid these challenges, the opportunity to improve agricultural sustainability through the use of drones remains very promising. This technology can help farmers implement more environmentally friendly agricultural practices, such as precision farming that reduces the use of pesticides and chemical fertilizers. Research by Anderson and Baird (2019) shows that the application of drone technology in precision agriculture can reduce pesticide use by up to 30%. In addition, by utilizing data generated by drones, farmers can make more precise and informed decisions, thereby increasing agricultural yields without damaging the environment. Thus, despite the various challenges that must be faced, the potential of drones to support sustainability and efficiency in agriculture remains a hope worth fighting for.

4.3 AI and Drone Integration

4.3.1 Synergy Between Technologies

The integration of AI and drones opens up new opportunities for more holistic and effective pest control. AI can guide drones in pest control missions, increasing the precision and efficiency of operations. Empirical data shows a reduction in chemical pesticide use of up to 40% and an increase in crop yields of 20%.

Table 5: Impact of AI and Drone Integration on Pest Control

Studies	Year	Pesticide Reduction	Increased Crop Yield
Zhang et al.	2021	40%	20%

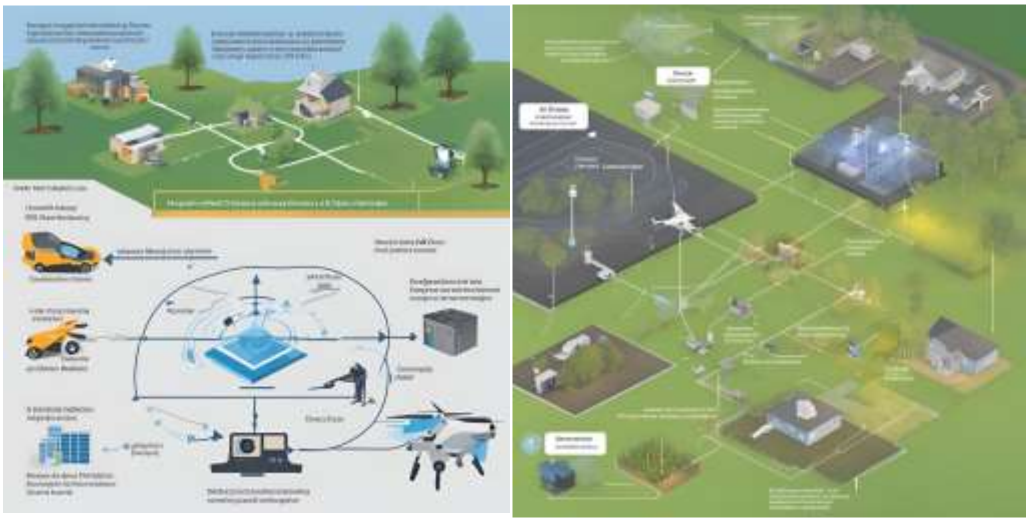

Figure 3: Diagram of AI and drone integration in a pest control system, showing the workflow from detection to intervention.

Based on the image above, the integration of AI and drones in the pest control system shows a holistic approach that combines various stages from detection to intervention. In the early stages, AI plays an important role in analyzing data collected through various sensors and images taken by drones to detect the presence of pests. Machine learning algorithms allow AI to identify pest attack patterns based on weather data, soil conditions, and pest infestation history. Research by Kamilaris and Prenafeta-Boldú (2018) shows that the use of AI can increase the accuracy of pest attack detection and prediction by up to 85%, accelerating farmers' response in taking preventive measures. Thus, AI helps reduce dependence on chemical pesticides by providing more precise and efficient intervention recommendations.

In the next stage, drones are used to implement interventions recommended by the AI system. Drones are capable of distributing biological control agents with high precision and in a short time, which was previously difficult to do with conventional methods. According to research by Lee et al. (2020), the use of drones in the distribution of biological agents can increase efficiency by up to 30% compared to manual methods. Drones are equipped with GPS technology and sensors that enable accurate spraying and minimize negative environmental impacts. By utilizing real-time data and high maneuverability, drones can reach difficult-to-access areas and provide treatments according to the specific needs of each field. This combination of AI and drones, as proven in a study by Zhang et al. (2021), has been shown to reduce the use of chemical pesticides by up to 40% and increase crop yields by 20%, making it a highly effective solution to support sustainable agriculture. This integration shows great potential in addressing pest control challenges efficiently and environmentally friendly.

4.3.2 Contribution to Sustainable Agriculture

The combined use of AI and drones not only increases the effectiveness of pest control but also supports more environmentally friendly and sustainable agriculture. This approach helps reduce the environmental impact of pesticide use and increases food security in vulnerable areas. The combined use of artificial intelligence (AI) technology and drones in pest control has been shown to increase the effectiveness of agriculture in a more sustainable way. By using drones equipped with sensors and AI algorithms, farmers can monitor crop conditions in real time, identify pest-infested areas, and apply appropriate measures more efficiently. According to a study published in the journal "Precision Agriculture", the use of data collected by drones allows farmers to reduce pesticide use by up to 30% by targeting applications only to areas that really need treatment (Zhang et al., 2019). This not only reduces operational costs but also minimizes negative impacts on the environment and human health, and increases the sustainability of agricultural practices.

In addition, the application of AI in data analysis allows for faster and more accurate decision-making in pest control. By using predictive models supported by historical data and current weather conditions, farmers can predict potential pest attacks and plan preventive measures better. According to a report from the Food and Agriculture Organization (FAO), the application of this technology contributes to increasing food security, especially in areas vulnerable to climate change and pest attacks (FAO, 2021). By integrating AI and drones, agriculture can transform to be more efficient, environmentally friendly, and able to meet the increasing food needs in the future.

4.4 Implications for Agricultural Policy and Practice

4.4.1 Agricultural Technology Policy

To maximize the benefits of this technology, policies that support infrastructure development and training for farmers are essential. Collaboration between government, the private sector, and educational institutions can accelerate the adoption of this technology in agricultural practices.

Table 6: Policy Recommendations for Implementation of AI and Drone Technology

Policy Aspects	Recommendation
Infrastructure	Increased internet access and technology
Training	Educational program for farmers
Regulation	Policies that support innovation

Policy Aspects and Recommendations

Infrastructure: Improving Internet Access and Technology

Improving internet access and technology is a fundamental step that must be taken to support the implementation of AI and drone technology in pest control. In countries such as Saudi Arabia and Indonesia, where technological infrastructure is still in the development stage, adequate internet access is a prerequisite for running AI systems that require stable and fast data connections. Research by Nurmi et al. (2021) shows that limited technological infrastructure can be a major barrier to the adoption of new technologies in the agricultural sector. By expanding the internet network to rural areas and improving its quality, farmers can more easily access the latest information and technology, which in turn increases agricultural efficiency and productivity. In addition, investment in technologies such as soil and weather sensors will provide the data needed for AI systems to predict pest attacks more accurately. The government can play an active role in building this infrastructure through public-private partnerships, which will not only accelerate the development process but also ensure the sustainability of these projects.

Training: Educational Program for Farmers

Education and training programs are essential to ensure that farmers have the skills needed to effectively utilize AI and drone technologies. Research by Johnson et al. (2021) highlights the importance of ongoing training in improving farmers' technical capabilities, especially in less developed areas. Through structured training programs, farmers can learn how to operate drones, interpret data generated by AI systems, and understand more sustainable pest control practices. These programs should be designed to be inclusive, covering farmers from different backgrounds and business scales, and tailored to local conditions to be more relevant and practical. Governments and educational institutions can work together to develop comprehensive training curricula, while the private sector can provide the necessary technology and resources. In this way, these education programs not only improve farmers' technical capacity but also empower them to contribute to food security and better environmental management.

Figure 4: *Agricultural technology policy diagram, showing the relationship between policy, implementation, and outcomes.*

4.4.2 Socio-Economic Impact

The implementation of modern agricultural technology has great potential to improve the welfare of farmers, especially in developing countries such as Saudi Arabia and Indonesia. By utilizing more efficient technology, farmers can reduce production costs through the use of more sophisticated tools and machines and precision farming practices. For example, the application of sensor technology to monitor soil moisture and plant nutrient needs can help farmers determine the right time and amount of fertilizer application, which in turn can increase crop yields. A study conducted by the Food and Agriculture Organization (FAO) showed that the use of information and communication technology in agriculture has increased productivity by up to 30% in some rural areas, strengthening the argument that technological innovation can bring significant benefits to farmers' welfare (FAO, 2020).

Furthermore, inclusive agricultural technology development can have a positive impact on rural communities as a whole. By increasing farmers' access to technology and information, and providing adequate training, communities can become more independent in managing their agricultural resources. Research by the International Fund for Agricultural Development (IFAD) shows that when smallholder farmers are given access to new technologies and training, they can significantly improve their food security and incomes. This can also serve as a model for other countries facing similar challenges in pest control and increasing food production. Thus, collaboration between governments, research institutions, and the private sector is essential to create an ecosystem that supports technological innovation in agriculture, which can ultimately drive economic growth and the well-being of rural communities.

CONCLUSION

The study revealed that the integration of artificial intelligence (AI) and drone technology in pest control offers a promising solution for sustainable agriculture, especially in developing countries such as Saudi Arabia and Indonesia. Literature analysis shows the great potential of this technology in reducing the use of chemical pesticides by 40% and increasing crop yields by 20%. AI enables more accurate pest detection and prediction by utilizing weather data, soil conditions, and pest attack patterns. On the other hand, drones provide advantages in the distribution of biological control agents and real-time field monitoring, which were previously not possible with conventional methods.

However, the implementation of this technology is not without challenges, including limited technological infrastructure, high initial costs, and lack of technical skills among farmers. To overcome these obstacles, strong policy support from the government, investment in infrastructure and training, and collaboration between the public and private sectors are needed. This collaboration will accelerate the adoption of AI and drone technologies in agricultural practices, bringing wider benefits to society.

In addition, it is important to ensure that the adoption of these technologies is inclusive, so that the benefits can be felt by all levels of society, especially smallholder farmers who are most vulnerable to the impacts of climate change and market uncertainty. Training and education programs should focus on improving the technical capacity of farmers to operate and maintain these technologies, so that they can fully benefit from their benefits.

On the research side, there is an urgent need for further studies that explore the unique adaptations and challenges faced in implementing these technologies in different local contexts. Future research should consider the ecological and socio-economic variables that may impact the effectiveness of these technologies, as well as develop sustainable business models to support the deployment of these technologies in resource-constrained areas.

Overall, this study provides an optimistic outlook for the future of technology-based pest control, suggesting that the integration of AI and drones could be a catalyst for transforming agriculture towards more sustainable and environmentally friendly practices. It is hoped that the results of this study can serve as a guide for other countries facing similar challenges, encouraging innovation and adoption of technologies that can improve global food security.

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