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Analysing the Potential of Agricultural Technology Integration in Crop Monitoring Systems to Improve the Efficiency of Soybean Cultivation

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Abstract: This study aims to integrate modern agricultural technology into soybean cultivation through the application of an Internet of Things (IoT)-based crop monitoring system combined with artificial intelligence (AI) and cloud-based data processing. The research was conducted at two experimental sites to evaluate system performance under different environmental conditions. IoT sensors and AI algorithms were utilized to monitor soil moisture, temperature, and plant health, optimize irrigation, detect pests, predict yield, and analyze plant health. Data collected included irrigation efficiency, pest control effectiveness, and plant health, which were analyzed using statistical methods. The results showed that the implementation of IoT-based monitoring technology significantly improved the technical efficiency of soybean farming by optimizing the use of land, fertilizer, and labor. Farms using monitoring technology achieved an average technical efficiency score of 0.991, higher than farms without technology, which only reached 0.920. In addition, the technology reduced water and fertilizer wastage, increased productivity, and supported data-driven agricultural decision-making. In conclusion, the application of IoT- and AI-based crop monitoring systems enhances the sustainability and productivity of soybean farming and provides an effective approach to improving agricultural efficiency in modern farming systems.

Keywords: Internet of Things; Crop Monitoring; Soybean Cultivation; Technical Efficiency; Precision Agriculture

Introduction

Soybean production in Indonesia remains relatively low compared to other soybean-producing countries in Asia, despite Indonesia being one of the largest soybean consumers. This situation is caused by several structural issues, including limited agricultural land, declining soil quality, the impacts of climate change, and the dominance of conventional agricultural practices by most farmers. Climate change has exacerbated these challenges through unpredictable rainfall patterns and extreme weather events, which directly impact crop growth, irrigation management, and the emergence of pests and diseases. This situation highlights the urgent need for more adaptive and efficient cultivation strategies to ensure sustainable soybean production.

Modern agricultural technology offers significant potential to address these challenges by increasing efficiency and productivity in soybean cultivation. Technologies such as sensors, the Internet of Things (IoT), artificial intelligence (AI), and cloud-based data systems enable the collection and analysis of real-time

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data on environmental and crop conditions. Through continuous monitoring of soil moisture, temperature, soil pH, and plant health, farmers can make more accurate and timely decisions regarding irrigation, fertilization, and pest control. Previous studies have shown that the integration of IoT-based monitoring systems can reduce resource waste, increase crop productivity, and support data-driven agricultural management (Rachmawati, 2020; Syahdan, 2023). However, despite the increasing adoption of smart agricultural technologies, their application in soybean cultivation in Indonesia remains limited, particularly in evaluating their impact on agricultural efficiency. Most existing studies focus on technology development or productivity improvement, while empirical analyses linking technology integration to technical, allocative, and economic efficiency are scarce. This gap highlights the need for research that not only applies monitoring technologies but also quantitatively assesses their contribution to cultivation efficiency in real-world farming conditions.

Based on these considerations, this study aims to analyze the potential for integrating agricultural technology into soybean crop monitoring systems, focusing on the use of IoT sensors and AI-based analytics to improve cultivation efficiency. By implementing and evaluating soil monitoring systems in two experimental fields, this study provides empirical evidence on how modern agricultural technologies can improve technical efficiency, resource utilization, and sustainability in soybean cultivation. These findings are expected to contribute to the development of smart and sustainable agricultural practices and support policy and decision-making for technology adoption in the Indonesian agricultural sector.

Modern agricultural technologies, such as sensors and the Internet of Things (IoT), improve the efficiency of soybean cultivation. The integration of these technologies enables real-time data collection and analysis, helping farmers make more informed decisions (Rachmawati, 2020). This technology is also used to monitor farmland and predict soybean plant growth conditions, improving agricultural planning such as fertilizer use, pest and disease control, and irrigation, the development of its application can be seen in table 1.

Table 1. Comparison of the Application of Monitoring Technology in Various Activities

Activities	Monitoring Technology (Article)					
	Plant Sensors and the Internet of Things (IoT)	Drones for Monitoring	Remote Sensing	Artificial Intelligence	Cloud Platform	Number of Monitoring Technology Articles
Land Preparation	30	16	11	18	11	94
Planting	33	15	10	18	9	85
Fertilization	17	9	6	10	4	46
Weed Management	11	7	4	7	6	35
Pest and disease control	11	13	8	9	5	57
Watering	20	5	3	4	1	33
Harvest	34	14	11	19	8	86

Source: Scientific journal database (PubMed, Google Scholar, IEEE Xplore), 2023 (Marina, et al. 2023)

This research aims to analyze the potential of agricultural technology integration in soybean crop monitoring systems, focusing on the use of sensors and IoT, to improve cultivation efficiency in the face of increasingly complex environmental challenges. With this holistic approach, it is expected that the technology developed can not only increase soybean productivity, but also provide sustainable solutions for the agricultural sector in Indonesia.

Research Method

This research is a continuation of the previous year's research with the following methods:

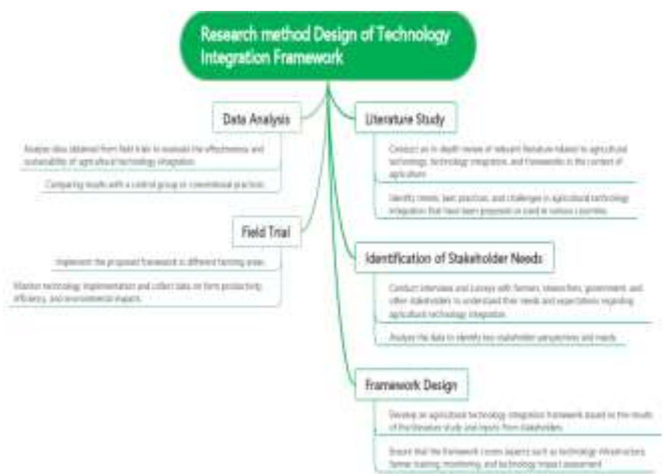

Figure 1. Design of Technology Integration Framework

Figure 1 presents the overall research framework used in this study. The framework begins with identifying key challenges in soybean cultivation, followed by system design and development using IoT sensors and artificial intelligence. The system is then implemented in experimental fields to collect real-time data, which are analyzed to evaluate cultivation efficiency and system effectiveness.

The study was conducted in five phases, in two soybean cultivation experimental fields. This study utilized IoT sensors, AI algorithms, and cloud-based data processing systems to monitor and analyze environmental factors such as soil moisture, temperature, and plant health. The crop monitoring system was developed using a combination of IoT devices (moisture sensors, temperature sensors) and AI for predictive analysis (Mathur, et al. 2023). The system was installed in two experimental sites to compare its effectiveness under different environmental conditions (Irmayani, et al. 2024).

a. Hardware: IoT sensors including soil moisture sensors, temperature sensors, and weather stations are installed in the fields.
b. Software: AI algorithms are applied to process sensor data and predict irrigation needs and potential pest attacks.

Data was collected on environmental conditions, system performance, and feedback from local farmers and agricultural experts. The main variables studied include:

a. Irrigation Efficiency: Measured by the system's ability to optimize water use.
b. Pest Control Effectiveness: Evaluated through the system's ability to detect and recommend pest control measures.
c. Plant Health: Analyzed using AI-based predictive models.
d. Statistical analysis, including descriptive statistics and correlation analysis, was used to evaluate the impact of the system on crop yields and overall farm efficiency.

Result and Discussion

SIMOTAN Testing Phase

The integration of modern agricultural technology through an automated monitoring system using soil moisture and soil pH sensors is effective in improving the efficiency of soybean cultivation. The following system circuit can be seen in Figure 2.

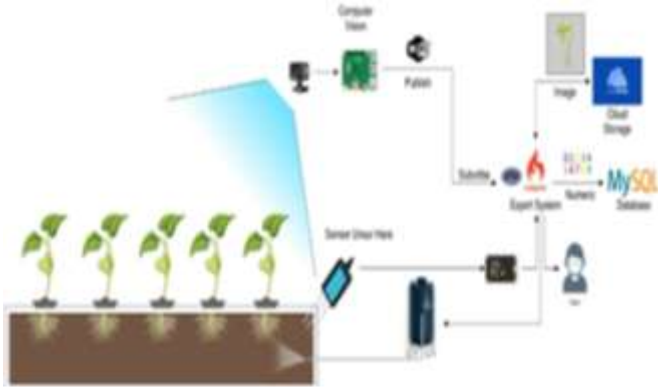

Figure 2. Development of Integrated Technology Model in Soybean Cultivation

This figure shows the architecture of the integrated monitoring system, including soil moisture sensors, soil pH sensors, IoT devices, cloud data storage, and a mobile application interface. Sensor data are transmitted in real time to the cloud platform for analysis and visualization, enabling automated irrigation control and continuous monitoring of soybean field conditions.

As shown in Figure 2, sensor nodes installed in the soybean field collect environmental data such as soil moisture and soil pH. These data are transmitted via IoT devices to a cloud-based platform, where they are processed and displayed through a mobile application. This system allows farmers to monitor field conditions remotely and make timely decisions related to irrigation and crop management.

The results of this study reinforce findings from previous studies on the benefits of technology integration in soybean cultivation to improve cost efficiency and productivity, as highlighted by Truong et al. (2019) and Hameed et al. (2021). This research shows that the use of soil moisture and soil pH sensors, as well as an Internet of Things (IoT) system integrated in a soybean field monitoring system, successfully increases crop productivity. The use of monitoring technology allows real-time monitoring of land conditions, in line with the opinion of Hameed et al. (2021) stated that this monitoring can help farmers detect early signs of pest, disease and weed infestation and make faster and more informed decisions.

The monitoring technology installed in the experimental fields not only helps farmers in managing automated irrigation, but also plays an important role in crop nutrient management through more efficient fertilization. As per the findings of Rahman & Biswas (2021), real-time data-based irrigation and fertilization settings from sensors help reduce water and fertilizer wastage, thereby optimizing resource utilization. The monitoring technologies integrated in this study helped to improve harvest quality and productivity of soybean crops, as revealed by Akhter et al. (2019). Real-time data on environmental conditions and crop growth enabled preventive action and better planning, which contributed to increased yields. Evaluation of the system's performance through feedback from farmers and agricultural experts showed that the system successfully reduced losses due to pests and diseases, in line with the findings of Li et al. (2020) on the benefits of technology in reducing production costs and increasing profits for farmers.

Based on the circuit scheme above, it is a design for a monitoring and control system for soil moisture, soil ph for automatic irrigation applications and soil monitoring in soybean fields Afi, et al.2023). The following circuit is presented in Figure 3.

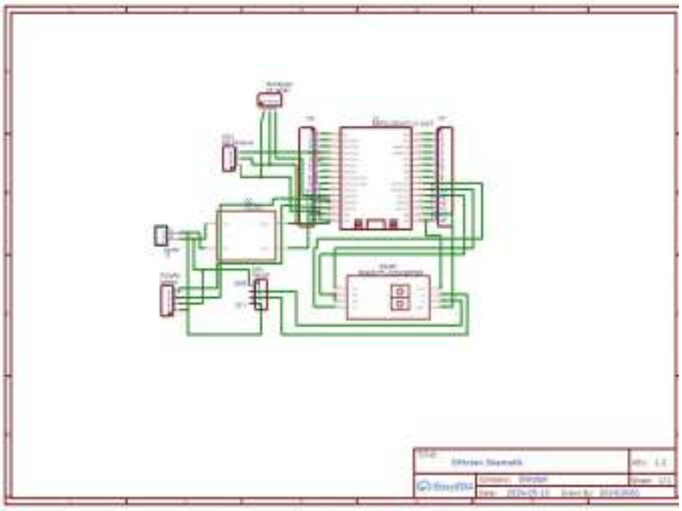

Figure 3. Design of Soil Moisture Control Monitoring System, Soil Ph Automatic Irrigation & Soil Monitoring Application on Soybean Crops.

This figure illustrates the control system design consisting of soil moisture and soil pH sensors, ESP32 microcontroller, RS485 communication module, water pump, and power supply. The system automatically activates irrigation when soil moisture falls below a predefined threshold. Figure 3 explains the working mechanism of the automatic irrigation system. The ESP32 microcontroller processes data received from soil sensors and controls the water pump based on predefined moisture thresholds, ensuring optimal water usage for soybean cultivation. This monitoring system is designed to optimize soybean cultivation by utilizing modern technology in the management of water resources and soil conditions (Chiranjeeb, et al.2022**)**. The system consists of several key components that are integrated with each other, working synergistically to provide accurate data and be responsive to the needs of the soybean crop.

Soil Moisture Sensor

The soil moisture sensor functions to measure the level of soil moisture with the labels "SOIL" and "SOIL moisture". This sensor can provide moisture readings in the form of analog signals, which are then sent to the microcontroller. The assumptions applied to this sensor are: Ideal soil moisture for soybean growth ranges from 20-30%. The sensor will measure soil moisture and provide accurate data for decision making.

ESP32 DEVKIT V1 DOIT

The ESP32 microcontroller serves as the brain of this system, with Wi-Fi and Bluetooth capabilities that support IoT applications. This microcontroller has an important role in: ESP32 will read the data from the humidity sensor, comparing it with a predefined threshold value (e.g. 25% humidity). If the humidity is below the threshold, the ESP32 will control the pump to perform automatic irrigation. Through connectivity capabilities, the ESP32 can transmit real-time moisture data to a mobile application for remote monitoring.

Water Pump

The water pump is used to irrigate the soil according to the measured moisture requirement. The control of the pump is done through an RS485-TTL Converter, which allows communication between the ESP32 and the pump. Some assumptions related to this pump are: The pump will operate automatically when the soil moisture is below 25% and will be turned off when the moisture reaches the desired level, for example 30%.

RS485-TTL Converter

This module serves as a communication link between the ESP32 that uses the TTL interface and the pump that may use the RS485 interface. RS485 technology is known to be resistant to interference and capable of sending data over long distances. The assumptions applied are: In bad weather conditions or in noisy environments, RS485 will still provide stable and reliable communication between the ESP32 and the pump.

Power Supply

The system requires two different power sources, 5V DC for the ESP32 and other components, and 12V for the pump. Assumptions regarding the power supply are: The system is designed to optimize energy use, where the resources used can be easily accessed and available in the field, supporting operational sustainability.

Figure 4. Illustration of Soil Monitoring System (Simotan) for Soybean Plants

This figure presents the SIMOTAN system architecture, showing sensor nodes, MQTT broker, cloud platform, and mobile application. The system enables real-time monitoring of soil conditions and supports efficient decision-making for irrigation and fertilization management.

This soil monitoring system for soybean crops is designed using Internet of Things (IoT) technology, which enables data collection and transmission from sensors installed in the field to an application on a mobile phone. The system consists of several main components, namely Sensor Nodes, which include soil pH sensors to measure acidity, NPK sensors that measure Nitrogen, Phosphorus, and Potassium nutrient levels in the soil, and soil moisture sensors to monitor moisture levels (Rahma, et al.2023). Data from these sensors is sent to an MQTT Broker, which serves as the communication hub, before being forwarded to a subscribed mobile app to display the data in real-time.

The system, known as SIMOTAN (Soil Monitoring System), also consists of a panel box containing electronic components to control the sensor nodes and communicate with the MQTT Broker. The soybean crop is the main monitoring object, with sensors placed around it to collect information on soil conditions. In a systematic way of working, the sensor nodes collect data and send it to the MQTT Broker using the MQTT protocol, which is then forwarded to the mobile application. Users can monitor the soil conditions of soybean plants continuously, allowing them to make better decisions regarding fertilization, irrigation, and other measures to maintain plant health. The benefits of this system include real-time monitoring, better decision-making, efficiency in fertilizer and water use, and increased crop productivity (Chitrao et al 2020). Thus, the application of this IoT-based soil monitoring system helps soybean farmers manage and monitor soil conditions, supporting sustainability and success in agricultural cultivation (Marina et al. 2023).

SIMOTAN Implementation Stage on Production Efficiency of Soybean Farming

Technical efficiency analysis using the Constant Returns to Scale (CRS) model in Data Envelopment Analysis (DEA) shows that soybean farms with cultivation monitoring technology are more efficient than farms without such technology. Farms with monitoring technology achieve technical efficiency values ranging from 1 to 0.966, with an average of 0.991 and 75% of them showing high efficiency. This technology allows farmers to maximize the use of inputs such as land area, seeds, fertilizers, pesticides, and labor optimally, thus approaching maximum efficiency. To see the proportion of technical efficiency of soybean farming, it is presented in Figure 5.

Figure 5. Proportion of Technical Efficiency of Soybean Farming in Majalengka Regency

In contrast, soybean farms without cultivation monitoring technology have lower technical efficiency values, ranging from 1 to 0.774, with an average of 0.920 and only 20% reaching the good efficiency level. This lower efficiency indicates inefficiencies in the use of inputs, which can include inappropriate use of fertilizers and pesticides, as well as suboptimal distribution of labor. This results in farms without monitoring technology having wasted resources and lower effectiveness in the cultivation process.

This difference in efficiency levels indicates that the application of cultivation monitoring technology has a significant impact on improving the technical efficiency of soybean farming. With monitoring technology, farms can manage resources more effectively, reduce wastage and increase productivity (Wahditiya et al. 2024). This supports data-driven decision-making, allowing farms with monitoring technologies to operate more efficiently and adapt better to environmental and market conditions, while strengthening their sustainability.

Allocative Efficiency

Analysis of allocative efficiency using the Variable Returns to Scale (VRS) model in Data Envelopment Analysis (DEA) shows that soybean farms without cultivation monitoring technology have higher allocative efficiency compared to farms using monitoring technology. Farms without monitoring technology have allocative efficiency values ranging from 1 to 0.895 with an average of 0.985, and 77% of these farms achieve a high level of allocative efficiency. Higher allocative efficiency indicates that farms without monitoring technology are more optimal in minimizing input costs such as land area, seeds, fertilizers, pesticides, and labor to achieve the same output (Siregar, 2027). To see the proportion of allocative efficiency of soybean farming, it is presented in Figure 6.

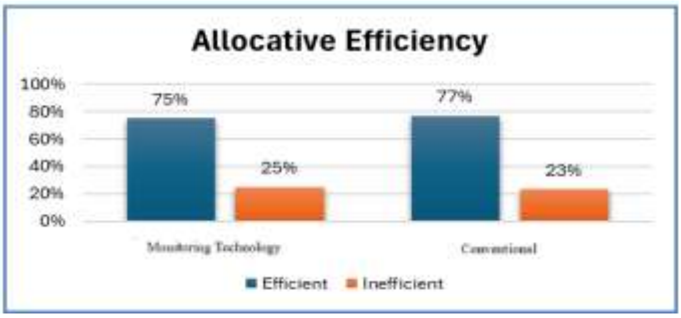

Figure 6. Proportion of Allocative Efficiency of Soybean Farming in Majalengka District

In contrast, soybean farms with cultivation monitoring technology had lower allocative efficiency values, ranging from 1 to 0.774 with an average of 0.920, and 75% of these farms achieved relatively lower levels of allocative efficiency. This suggests that while monitoring technologies can improve technical efficiency, their application may not always be optimal in terms of cost allocation. Factors such as additional costs for technology, training and maintenance may reduce the allocative efficiency of farms with monitoring technology compared to farms without technology that may be simpler and more straightforward in their cost management.

This difference in allocative efficiency highlights that cultivation monitoring technologies, while effective in improving technical efficiency, may require initial investment and operational costs that are not always worth the cost savings in the short term. Farms without monitoring technologies, with more conventional cost management approaches and more direct input costs, are able to allocate their resources more efficiently from a cost perspective. It is therefore important to consider the balance between technical and allocative efficiency when evaluating the adoption of new technologies in farming practices.

Economic Efficiency

Economic efficiency is the result of a combination of technical efficiency and allocative efficiency. This means that if farmers are technically and allocatively efficient, then they have achieved economic efficiency. Economic efficiency can be realized when the use of production factors produces maximum output at minimal cost. To see the proportion of economic efficiency of soybean farming in Majalengka Regency, it is presented in Figure 7.

Figure 7. Proportion of Economic Efficiency of Soybean Farming in Majalengka District

The results of the economic efficiency analysis, which is the product of technical efficiency and allocative efficiency, show that soybean farming with cultivation monitoring technology is more efficient than farming without such technology. Farms with monitoring technology had economic efficiency values ranging from 1 to 0.966 with an average of 0.983 and 50% of these farms achieved high economic efficiency. This indicates that the combination of optimal input use and adequate cost control enabled these farms to achieve high productivity levels while minimizing production costs. Cultivation monitoring technology assists farmers in more precise management, such as the timing and amount of inputs required, resulting in higher economic efficiency.

In contrast, soybean farms without cultivation monitoring technology showed lower economic efficiency, with values ranging from 1 to 0.774, averaging 0.905, and only 17% of these farms achieved adequate economic efficiency. Although allocative efficiency was higher on farms without monitoring technology, inefficiencies in input use reduced overall economic efficiency. The use of monitoring technology optimizes the production process by reducing wastage and increasing the effectiveness of inputs such as seeds, fertilizers, pesticides, and labor, while the no-technology approach tends to lead to less structured resource management (Marina, et al. 2020).

This significant difference in economic efficiency indicates that cultivation monitoring technologies provide substantial economic benefits in soybean farming. These technologies allow for smarter and more efficient input utilization and operational cost savings that ultimately increase farmers' profit margins. While high allocative efficiency in farms without technology indicates good cost control, lack of technical efficiency results in overall inefficiency. Therefore, the application of cultivation monitoring technologies significantly supports improved economic performance by increasing productivity and minimizing costs, making these farms more competitive and sustainable in the long run.

Discussion

Technology integration in improving the efficiency of soybean cultivation. In testing the Soil Monitoring System (SIMOTAN) conducted in two experimental fields, the use of IoT sensors and AI algorithms proved to provide significant benefits in monitoring and managing environmental factors. The results support previous findings by Truong et al. (2019) and Hameed et al. (2021) who emphasised that modern technology can assist farmers in improving productivity and cost efficiency. The designed monitoring system successfully improved irrigation efficiency, pest control effectiveness, and plant health. The use of soil moisture and pH sensors integrated with the IoT system allows real-time monitoring of field conditions. This is in accordance with the opinion of Hameed et al. (2021) who stated that real-time monitoring helps in early detection of pest and disease infestation, as well as taking the necessary quick action. In addition, the system supports more efficient crop nutrient management through automatic irrigation, as suggested by Rahman & Biswas (2021). Real-time data from sensors allows farmers to make informed decisions that can reduce water and fertiliser wastage, and thus increase crop yields, as stated by Akhter et al. (2019). Evaluation of the system's performance through feedback from farmers and agricultural experts shows that SIMOTAN can reduce losses due to pests and diseases, in line with the research of Li et al. (2020) who highlighted the positive influence of technology in lowering production costs. These results suggest that monitoring technologies not only serve to increase crop yields, but also support the sustainability of farming practices.

Technical efficiency analysis shows that soybean farms applying monitoring technology have higher technical efficiency values, ranging from 1 to 0.966, with an average of 0.991. This indicates that this technology allows farmers to maximise the optimal use of inputs. In contrast, farms without monitoring technology had lower technical efficiency, ranging from 1 to 0.774, and only 20% achieved a good level of efficiency. This suggests that the application of monitoring technology greatly contributes to improving technical efficiency, reducing wastage and increasing farm productivity. However, the analysis of allocative efficiency shows that farms without monitoring technology have higher allocative efficiency, with an average of 0.985 and 77% reaching the high efficiency level. Although monitoring technology improves technical efficiency, additional costs for technology, training and maintenance may be a factor affecting allocative efficiency. This indicates that there is a trade-off between technical efficiency and allocative efficiency, where the implementation of monitoring technologies needs to be accompanied by appropriate strategies to optimise costs and outcomes. The application of IoT and AI-based monitoring systems has the potential to improve the efficiency and productivity of soybean cultivation. However, challenges in terms of cost and resource allocation remain to be addressed so that these technologies can be implemented sustainably and provide maximum benefits to farmers. Future steps should focus on reducing technology costs and training to ensure that farmers can optimally utilise these technologies, thus supporting sustainability and increased agricultural yields in the future.

Conclusion

The application of monitoring technology to soybean cultivation has been shown to provide significant technical and economic benefits. Research shows that soybean farming with monitoring technology has better cost efficiency, indicated by a Revenue-Cost Ratio (RCR) of 2.71 compared to 2.31 in conventional systems. This technology increases productivity and yields through real-time monitoring of land conditions, efficient use of air and fertilizer, and more precise pest and disease control. Meanwhile, farming without monitoring technology shows lower allocative efficiency and potentially wastes resources. Therefore, the application of monitoring technology can be recommended as a strategy to increase efficiency, productivity, and reduce the risk of agricultural waste.

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Author Contributions

Conceptualization, I.M. and A.B.; methodology, I.M. and K.R.I.; software, A.B.; validation, D.S., A.K. and M.; formal analysis, I.N.H. and I.M.; investigation, I.M. and A.B.; resources, I.M.; data curation, A.B. and I.N.H.; writing—original draft preparation, I.M.; writing—review and editing, I.M., A.B. and M. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest
The authors declare no conflict of interest.

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