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Enhancing Mushroom Yield Productivity and Cultivation Efficiency with Fuzzy Logic and Internet of Things

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ABSTRAK

Penelitian ini memaparkan pengembangan dan implementasi sistem asisten cerdas untuk meningkatkan produktivitas dan efisiensi budidaya jamur tiram. Sistem ini memanfaatkan teknologi Logika Fuzzy dan IoT untuk mengoptimalkan kondisi lingkungan di dalam kumbung budidaya jamur. Tujuan penelitian meliputi pengembangan sistem asisten cerdas dan evaluasi dampaknya terhadap produktivitas dan efisiensi jamur tiram. Studi ini menggunakan pendekatan Penelitian dan Pengembangan (R&D) dengan menggunakan model Waterfall untuk pengembangan sistematis. Kerangka konseptual mencakup analisis terhadap tantangan yang ada dalam budidaya jamur yang mengarah pada identifikasi solusi melalui integrasi Logika Fuzzy dan IoT. Sistem ini terdiri dari *node sensor* untuk pengumpulan data, *node collector* untuk pemrosesan data, dan mekanisme penyiraman otomatis yang dikontrol oleh algoritma Logika Fuzzy. Implementasi sistem asisten cerdas melibatkan instalasi dan konfigurasi komponen sistem secara fisik di dalam kumbung budidaya jamur. Pengujian dilakukan melalui pengujian *black box*, memastikan fungsionalitas dan efektivitas sistem. Implementasi sistem ini menunjukkan peningkatan signifikan dalam produktivitas panen, dengan peningkatan total hasil jamur sebesar 37,4% dan peningkatan yang mencolok dalam efisiensi waktu dan tenaga kerja, keduanya sebesar 60%. Peningkatan ini menonjolkan efektivitas sistem dalam mencapai kondisi pertumbuhan yang konsisten dan optimal, menekankan potensi kombinasi IoT dan Logika Fuzzy dalam pertanian. Kesimpulannya, penelitian ini berhasil mencapai tujuannya dengan mengembangkan sistem asisten cerdas yang meningkatkan produktivitas dan efisiensi budidaya jamur tiram. Temuan ini menunjukkan implikasi yang menjanjikan untuk integrasi teknologi canggih dalam praktik pertanian.

Kata kunci: Sistem asisten cerdas, Budidaya jamur tiram, Logika Fuzzy, IoT, Peningkatan produktivitas, Optimasi lingkungan

ABSTRACT

This research presents the development and implementation of an intelligent assistant system to enhance the productivity and efficiency of oyster mushroom cultivation. The system utilizes Fuzzy Logic and IoT technologies to optimize environmental conditions in mushroom cultivation chambers. The research objectives include developing the intelligent assistant system and evaluating its impact on oyster mushroom productivity and efficiency. The study employs a Research and Development (R&D) approach, utilizing the Waterfall model for systematic development. The conceptual framework encompasses the analysis of existing challenges in mushroom cultivation, leading to the identification of solutions through the integration of Fuzzy Logic and IoT. The system comprises sensor nodes for data collection, a collector node for data processing, and an automated watering mechanism controlled by Fuzzy Logic algorithms. Deployment of the intelligent assistant system involves installing and configuring system components in mushroom cultivation chambers. Testing is conducted through black box testing, ensuring the functionality and effectiveness of the system. The implementation of this system demonstrated a significant improvement in yield productivity, with a 37.4% increase in total mushroom yield and notable enhancements in time and labor efficiency, both by 60%. These improvements highlight the system's effectiveness in achieving consistent and optimal growth conditions, underscoring the potential of combining IoT and Fuzzy Logic in agriculture. In conclusion, the research successfully achieves its objectives by developing an intelligent assistant system that enhances oyster mushroom cultivation productivity and efficiency. The findings suggest promising implications for integrating advanced technologies in agricultural practices.

***Keywords*:** Intelligent assistant system, Oyster mushroom cultivation, Fuzzy Logic, IoT, Productivity enhancement, Environmental optimization

INTRODUCTION

In addressing the environmental sensitivity of oyster mushroom cultivation, this research draws upon various technological and methodological insights, aiming to construct an Intelligent Assistant system that leverages IoT, AI, and other digital technologies. The endeavor at Jamur Hidayah, managed by Mr. Toni Hidayat since January 2010, illustrates the substantial potential and prevailing challenges within the agricultural sector, particularly in maintaining optimal growth conditions for oyster mushrooms, necessitating temperatures between 22-30°C and humidity levels of 80%-90% for peak productivity [1].

The development of the proposed system is guided by the Waterfall Development Method, emphasizing a linear and sequential approach to ensure each phase is thoroughly addressed before proceeding to the next. This method provides a structured framework for the research, ensuring clarity and orderliness in the development process [2]. Black Box Testing is employed to validate the software's functionality and reliability. This testing strategy focuses on the external workings of the software, assessing its performance based on expected outcomes without the need to examine its internal code structure [3], [4].

Technological components integral to the system's functionality include IoT, which facilitates real-time environmental monitoring through interconnected devices. IoT's capability to gather and process real-time environmental data is crucial for maintaining the precise conditions required for mushroom cultivation [5]. Fuzzy Logic is implemented as the decision-making core of the system, enabling it to interpret the often imprecise environmental data and make informed decisions on adjusting conditions to optimize mushroom growth. This AI technique is essential for processing complex, variable data and implementing nuanced control over the cultivation environment [6], [7].

Furthermore, the system's efficiency in data communication is bolstered by the use of Wireless Sensor Networks (WSNs) and the ESP-Now protocol. WSNs offer a robust framework for deploying sensor nodes throughout the cultivation area, ensuring comprehensive coverage and data collection on key environmental parameters. This network is pivotal in gathering detailed, localized data for precise environmental control [8], [9]. The ESP-Now protocol, specifically designed for short packet transmissions, enhances the system's responsiveness by reducing data transmission delays, thereby enabling faster adjustments to the cultivation environment based on real-time data [10], [11].

By integrating these components, each critical to the system's overall functionality, the research aims to address the yield inconsistency challenges faced by Jamur Hidayah, thereby enhancing productivity and operational efficiency. This initiative aligns with Indonesia's Industry 4.0 goals and sets a precedent for applying intelligent agricultural practices, demonstrating the potential of advanced technologies to revolutionize traditional farming methods. This research aims to illustrate the feasibility and benefits of adopting IoT, AI, and digital technologies in agriculture, contributing to the sector's evolution towards greater sustainability and efficiency.

METHOD

Type of Research

This study employs a Research and Development (R&D) approach, instrumental in creating or enhancing new products. R&D is a systematic process combining the discovery of new knowledge and its application to develop more effective products, processes, or technologies [12]. In the context of this research, R&D is utilized to develop and test the effectiveness of an Intelligent Assistant System for oyster mushroom cultivation, leveraging IoT and Fuzzy Logic.

The product of this research is a tool for helping oyster mushroom farmers maintain optimal conditions for oyster mushrooms to grow. This tool leverages IoT and Fuzzy Logic for the control system and uses a Telegram bot as a user-friendly interface. This stack allows mushroom cultivators to maintain optimal growth conditions and increase yield and cultivation efficiency.

Research Procedure

This research adopts the Waterfall model, a classic development approach. The Waterfall model is systematic and sequential, ensuring that each phase is thoroughly completed before moving on to the next. It is particularly well-suited to environments where requirements are well-understood, and changes will be minimal during development. As applied in this research, the development phases include the communication, Planning, Modeling, Construction, and Deployment stages [2].

Location and Time of Research

This research was conducted from June 1 to September 20, 2021. The research occurred at the Information Technology Program, Yogyakarta State University, and at the researcher's home. Testing and data collection for the study were carried out at Jamur Hidayah.

Research Subjects

This study focuses on two key categories of research subjects integral to implementing and evaluating the Intelligent Assistant System for oyster mushroom cultivation. The primary subjects encompass the cultivation environment at Jamur Hidayah, comprising the physical space where oyster mushrooms are grown, alongside factors like temperature and humidity. Understanding and optimizing this environment is crucial for successful mushroom cultivation and assessing the system's impact.

In addition to the cultivation environment, secondary subjects include the mushroom farm staff, notably individuals like Mr. Toni Hidayat and his wife, who are actively involved in the day-to-day operations at Jamur Hidayah. These individuals play a vital role in interacting with the Intelligent Assistant System, providing essential insights into its usability and effectiveness. Their feedback offers valuable perspectives on how well the system integrates into existing workflows and enhances overall productivity.

Data Collection Method

Data collection for this study employs a multifaceted approach to gather qualitative and quantitative insights into the implementation and effectiveness of the Intelligent Assistant System. Structured interviews were conducted with primary stakeholders, particularly Mr. Toni Hidayat, to delve into qualitative aspects such as the challenges encountered in mushroom cultivation and operational intricacies. These interviews focus on changes in maintenance routines, duration of chamber visits, and perceived impacts on labor and time efficiency resulting from integrating the new system.

Simultaneously, IoT sensors are being deployed within the mushroom cultivation environment to capture continuous data on crucial parameters like temperature and humidity. This quantitative data is fundamental for evaluating the effectiveness of the Intelligent Assistant System in environmental control. By monitoring these parameters in real time, researchers can assess the system's ability to maintain optimal growing conditions for oyster mushrooms.

Furthermore, a Telegram chatbot is utilized for daily digital logging of mushroom crop yields, streamlining the data recording process. This innovative approach ensures the timely and accurate documentation of yield quantities, which is essential for evaluating productivity enhancements following the implementation of the Intelligent Assistant System. This comprehensive data collection methodology aims to provide a holistic understanding of the system's impact on mushroom cultivation productivity by leveraging qualitative insights from interviews and quantitative data from IoT sensors and digital logging.

Data Analysis Technique

The data analysis technique employed in this study focuses on evaluating various aspects of productivity, labor efficiency, time efficiency, and profit increase resulting from implementing the Intelligent Assistant System in oyster mushroom cultivation.

To assess productivity increase, the study calculates the percentage increase in mushroom yields post-implementation using the formula:

$$Increase\ in\ productivity = \frac{increase\ in\ harvest\ yield}{initial\ harvest\ yield} \times 100\%$$

This metric provides a quantifiable measure of the improvement in mushroom yields facilitated by the intelligent system.

Labor efficiency is evaluated by measuring the reduction in manual labor required for mushroom cultivation with the new system. The formula used is:

$$Labor\ efficiency = 100\% - \frac{energy\ with\ tool}{conventional\ energy} \times 100\%$$

This calculation assesses the decrease in labor intensity attributed to adopting the Intelligent Assistant System.

Time efficiency for partners is assessed by comparing the maintenance time required with and without the tool. The formula employed is:

$$Time\ efficiency = 100\% - \frac{maintenance\ time\ with\ tool}{maintenance\ time\ without\ tool} \times 100\%$$

This analysis measures the reduction in time spent on mushroom cultivation activities after implementing the technology.

RESULT AND DISCUSSION

Communication

The research commenced with the communication phase, aiming to identify the fundamental issues or needs of oyster mushroom cultivators regarding challenges in achieving optimal yield productivity and efficiency. Through preliminary interviews with mushroom cultivators, a requirements analysis was conducted to understand their cultivation practices and challenges comprehensively. Insights gleaned from these interviews highlighted inefficiencies in manual irrigation practices, time-consuming maintenance activities, market dynamics, and financial constraints.

Based on this communication stage, it became apparent that the mushroom cultivation process faces challenges related to manual irrigation and environmental monitoring, leading to inefficiencies in time and labor utilization. These insights were the foundation for conducting a comprehensive analysis to identify the necessary features and functionalities for developing an intelligent assistant system tailored to enhance productivity and efficiency in oyster mushroom cultivation.

The findings from the needs analysis revealed several non-functional requirements, particularly regarding hardware components utilized for the development and deployment of the intelligent assistant system. These components included a laptop, ESP8266 NodeMCU V3 microcontrollers, DHT11 sensors, and a 2-channel relay module. Each of these components played a crucial role in enabling data collection, transmission, and control within the mushroom cultivation environment, facilitating the decision-making processes of the system.

Planning

Effective planning is crucial to the success of any development project. In this research, the planning phase ensured that the project progressed efficiently and that the time estimates for tool creation were accurate. The planning for the creation of the Intelligent Assistant System consisted of several critical steps shown in Table 1:

Table 1.Research Planning

No.	Activity	Week
1	Site Survey	1
2	Procurement of Tools and Materials	2
3	Construction and Installation of Tools	3-4
4	Training the Partners on Tool Use	4
5	Implementation 1	4
6	Evaluation and Refinement	5
7	Implementation 2	6-16
8	Program Evaluation	16
9	Tool Monitoring	6-16

Modelling

The modelling phase aimed to represent the information implemented in the tool through frameworks or diagrams, providing a visual depiction of the system architecture and interactions among components. This phase is critical for understanding how the Intelligent Assistant System functions.

System Architecture Design

The system architecture design delineated the overall structure of the Intelligent Assistant System, incorporating high-level components such as the Node Collector and Node Sensor. The system architecture diagram in Figure 1 illustrates the operational flow of the system, which relies on a network of sensor and collector nodes.

The operational flow of the Intelligent Assistant System unfolds through several key stages: Firstly, sensor nodes strategically placed within the mushroom cultivation chamber collect essential temperature and humidity data crucial for oyster mushroom growth. This data is transmitted to the collector node via the efficient ESP-Now protocol, facilitating swift communication. Upon reception, the collector node engages Fuzzy Logic algorithms to process the data, precisely determining the watering requirements for the mushroom chamber. In automatic mode, hourly checks are conducted, and if watering is stated necessary, the collector node activates the watering system using a relay module. The system offers manual control through a Telegram bot, allowing cultivators to execute watering or other adjustments as needed. Moreover, the collector node sends hourly reports to cultivators via the Telegram bot, detailing temperature and humidity levels and storing this information in a monitoring database through an API for comprehensive historical data analysis and trend monitoring.

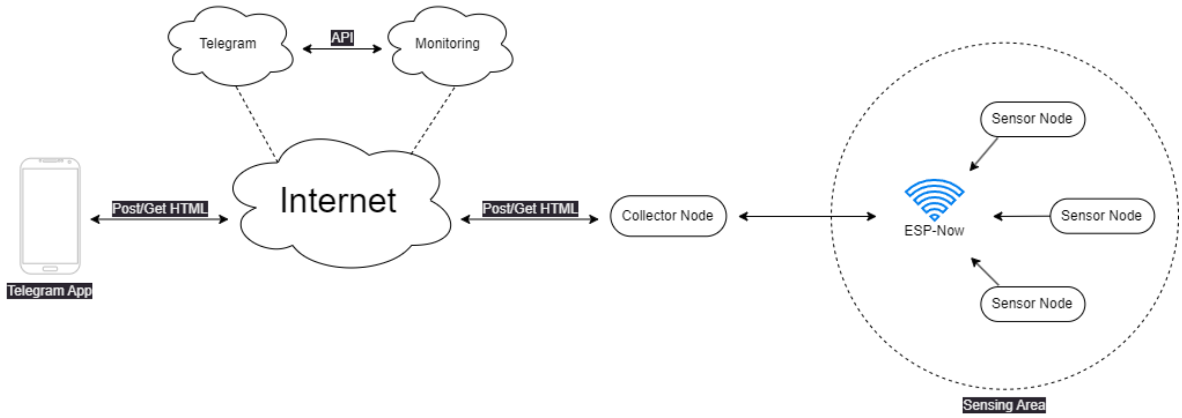

Figure 1. System Architecture Diagram

Electronic Circuit Design

The electronic circuit design detailed the wiring and connections between the hardware components, such as the ESP8266 NodeMCU, DHT11 sensors, and the relay modules. It provided a circuit diagram critical for the accurate assembly and installation of the physical components. The wiring of the Collector Node and Sensor Node is shown in Figure 2.

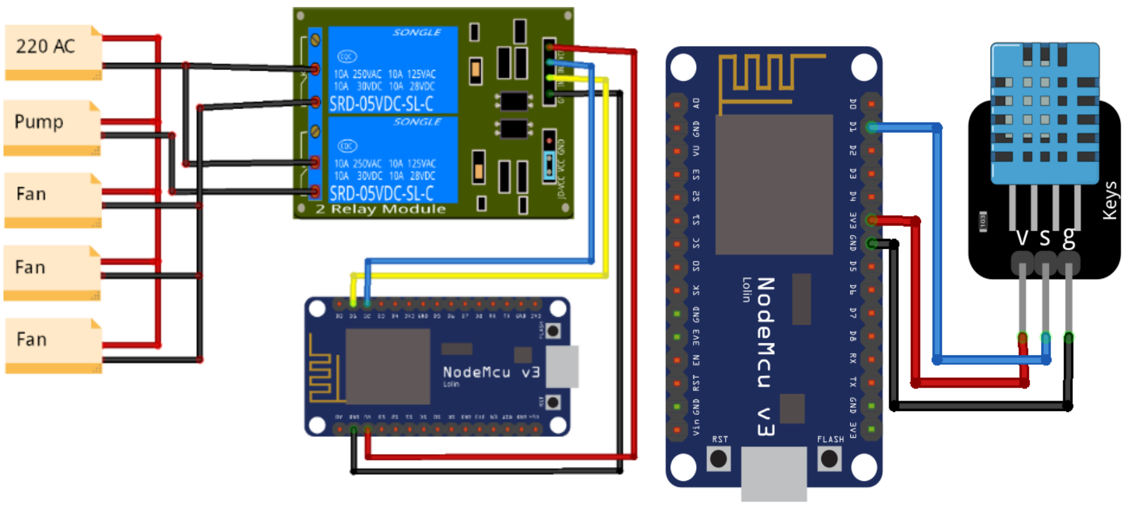

Figure 2. Collector Node Wiring (Left) Sensor Node Wiring (Right)

Implementation Design for Equipment Placement in Mushroom Chamber

This design focused on the physical placement of equipment within the mushroom cultivation environment. It took into consideration the environmental conditions, ease of access for maintenance, and optimal positioning for sensor accuracy and relay operation. The placement of the Collector Node, Sensor Node, Pump, Fan, and MiFi is shown in Figure 3.

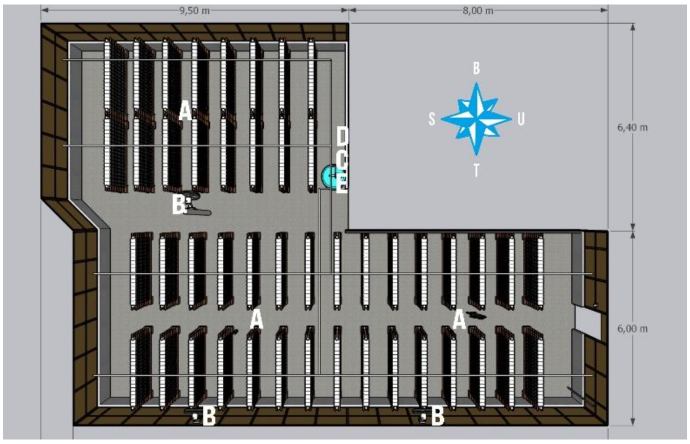

Figure 3. Mushroom Cultivation Chamber Plan

In the setup, several components are identified by specific codes: Code A refers to the Sensor Node, which is positioned in a hanging configuration within the cultivation area to monitor environmental conditions. Code B denotes the Fan installed within the wall of the setup, contributing to the regulation of air circulation. Similarly, Code C represents the Collector Node, also integrated into the wall, responsible for collecting and processing data from the sensor nodes. Code D designates the MiFi device, which is also installed within the wall, facilitating internet connectivity for data transmission. Lastly, Code E signifies the Pump, a component utilized for watering purposes within the cultivation system. Each of these coded components plays a distinct role in ensuring the functionality and efficiency of the setup for optimal mushroom cultivation.

Fuzzy Logic Design for Watering System

The intelligent assistant system integrates a Fuzzy Logic control strategy to ascertain the optimal watering duration for oyster mushroom cultivation, following the Sugeno method. This Fuzzy Logic design incorporates linguistic variables, membership functions, and rules to guide decision-making based on environmental data. Firstly, linguistic variables for temperature, humidity, and watering duration are defined, categorizing conditions into Cold, Moderate, and Hot for temperature; Dry, Normal, and Wet for humidity; and Off, Little, and A Lot for watering duration. Subsequently, Fuzzy Logic rules are established to determine watering duration based on humidity and temperature combinations, as outlined in Table 2.

Table 2. Fuzzy Logic Rules

Humidity	Temperature		
	Cold	**Moderate**	**Hot**
Dry	Little	Little	A Lot
Normal	Off	Off	Little
Wet	Off	Off	Off

Finally, defuzzification employs the Zero-Order Center of Area (zCOA) method to convert fuzzy output into a precise watering time in milliseconds, ensuring accurate adjustments to cultivation conditions. This comprehensive Fuzzy Logic design enhances the system's ability to maintain optimal environmental parameters for successful oyster mushroom cultivation.

Construction

During the construction phase, the focus was on the physical assembly of the system's components and the implementation of their functionalities, which are crucial for translating designs and plans into a functional system.

Firstly, the Collector Node assembly was executed, involving wiring implementation to ensure proper connection of the 2-Channel Relay Module to the NodeMCU. Subsequently, programming implementation was carried out using the Arduino IDE to program the NodeMCU. This programming encompassed integrating Fuzzy Logic for decision-making and controlling the relay module for the watering system. Additionally, the Telegram Bot was set up to establish communication with the collector node, programmed to send and receive commands, facilitating both automatic and manual control over the system, as well as relaying environmental data and alerts to the user, as illustrated in Figure 4.

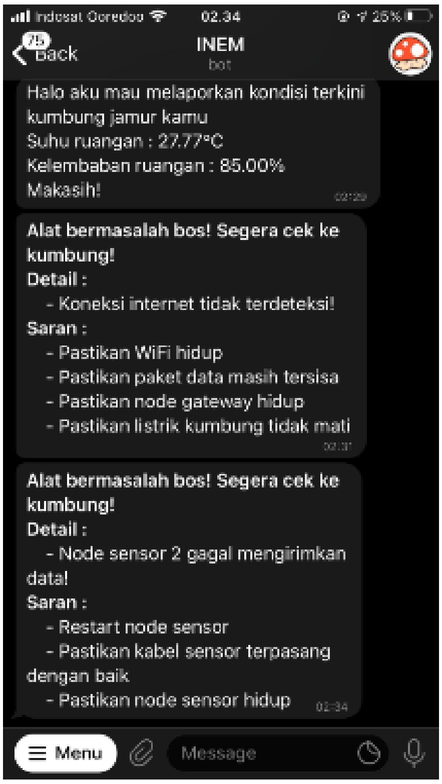

Figure 4. Telegram Bot

Following construction, testing was conducted utilizing black box testing methods to evaluate the system's functionality against the defined requirements, ensuring the system's reliability and effectiveness.

Various test cases are executed to ensure the system's functionality, reliability, and user-friendliness across different scenarios. Environmental data collection is rigorously tested, confirming accurate measurement, transmission, reception, and processing. Fuzzy Logic processing is evaluated for its decision-making accuracy and ability to adjust watering durations accordingly. The automatic watering system is validated for its activation and reliability, while manual mode operation ensures responsiveness and correctness in executing commands. Data reporting and logging are examined for consistency and accuracy in scheduled reporting and logging of received reports. Overall system integration undergoes end-to-end testing to ensure seamless functionality, while performance under different conditions showcases reliability and robustness. Usability and user experience are assessed, with end-users finding the Telegram bot interface intuitive and easy to use. Scalability and robustness testing confirm the system's ability to handle increased data loads and operate reliably under stress testing scenarios. Error handling and recovery mechanisms are verified, with the system demonstrating effective error detection and recovery. Overall, the transition phase validates the system's readiness for deployment, ensuring its effectiveness and reliability in real-world usage scenarios.

Deployment

In the Deployment phase, the Intelligent Assistant System is physically installed and configured within the mushroom cultivation chamber to seamlessly integrate with the existing infrastructure, ensuring optimal conditions for oyster mushroom cultivation.

Collector Node Installation

The collector node is mounted in a centralized location within the chamber to facilitate optimal data collection. It is securely positioned and provides access to a power source. Additionally, the pump and fan are connected to the relay module according to the wiring diagram. A successful installation is depicted in Figure 5.

Figure 5. Installed Collector Node

Sensor Node Placement

Sensor nodes are strategically installed within the chamber to measure temperature and humidity accurately. Placement considerations include positioning the nodes away from direct airflow or heat sources to prevent skewed readings. Secure mounting ensures stability and an unobstructed view of the cultivation environment is maintained. An illustration of successful sensor node installation is presented in Figure 6.

Figure 6. Installed Sensor Node

Result on Mushroom Yield Productivity

After one month of implementing the equipment in the partner's mushroom chamber, containing 10,000 bags of mushroom substrate, a comparison of daily harvest yields was conducted, as illustrated in Figure 7.

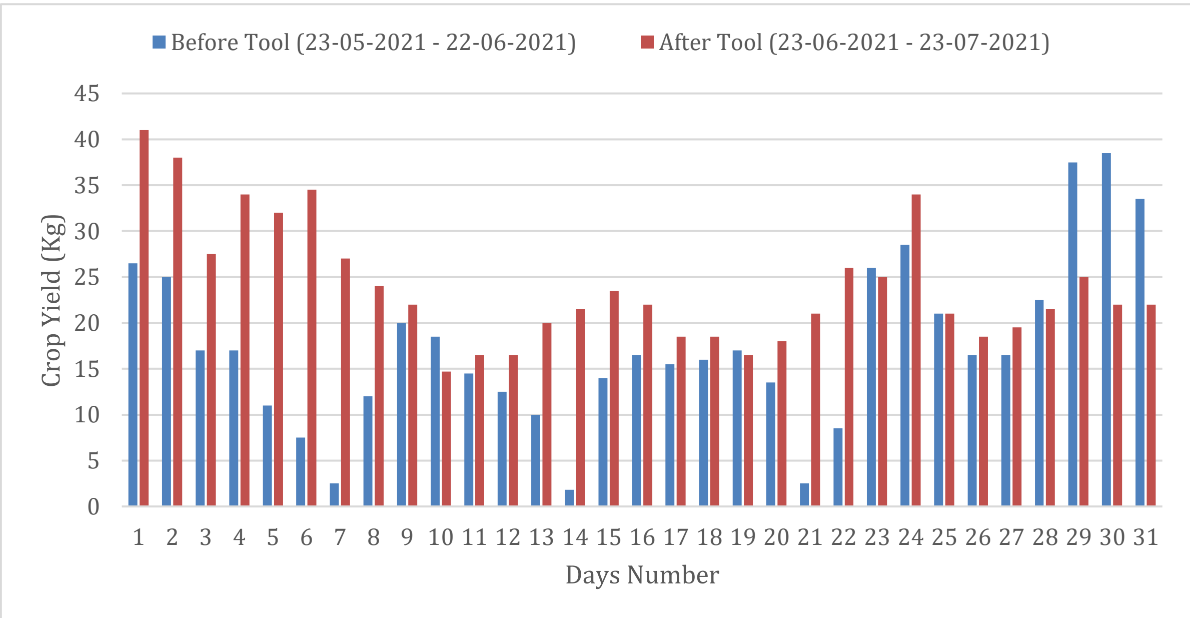

Figure 7. Comparison of Daily Harvest

The comparison highlighted a significant enhancement in daily mushroom yield. Prior to the equipment's utilization, there was a notable decrease in mushroom yield every seven days. However, following implementation, mushroom yields exhibited more excellent stability, accompanied by a noticeable increase in the total yield. The total yield before equipment usage amounted to 539.8 kg, which subsequently rose to 741.7 kg after equipment utilization, indicating a 37.4% increase in yield productivity.

In the second month of equipment implementation, commencing from July 24, 2021, the government implemented PPKM (Community Activity Restriction) measures, impacting the partner's business. Consequently, the market was unable to absorb the entire harvest, prompting the partner to reduce the number of mushroom substrate bags in the chamber from 10,000 to 8,000. Despite the reduction in baglog quantity, the yield productivity of mushrooms per baglog surged by 32.07%, as depicted in Figure 8.

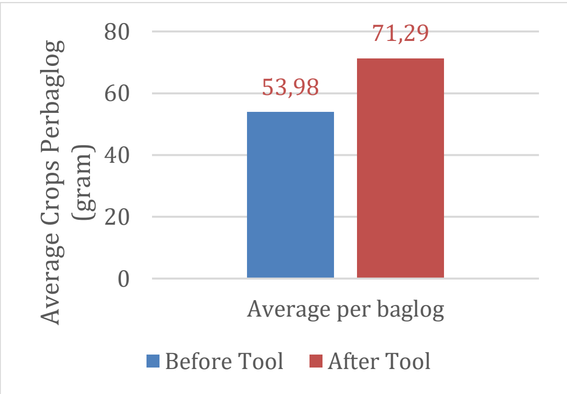

Figure 8. Yield Productivity per Baglog

Result on Time Efficiency of Maintaining the Mushroom Cultivation Environment

Before the equipment implementation, the partner visited the mushroom chamber five times daily for tasks like watering and harvesting, spending 45 minutes per visit. However, after implementing the equipment, the partners' visits were reduced to twice a day for harvesting. To evaluate the partner's time efficiency post-implementation, a comparison was made between the total time spent visiting the chamber before and after equipment usage. Using the formula:

$$Time\ Efficiency = 100\% - \frac{Time\ with\ Equipment}{Time\ without\ Equipment} \times 100\%$$

Substituting the values:

$$Time\ Efficiency = 100\% - \frac{2\ \times 45\ minute}{5\ \times 45\ minute} \times 100\%$$

$$Time\ Efficiency = 60\%$$

Hence, there was a remarkable 60% improvement in time efficiency post-implementation, enabling the partner to allocate more time to other activities.

Result on Labor Efficiency of Maintaining the Mushroom Cultivation Environment

Similarly, labor efficiency was assessed based on the frequency of partner visits to the mushroom chamber. Using the formula:

$$Energy\ Efficiency = 100\% - \frac{Visits\ with\ Equipment}{Visits\ without\ Equipment} \times 100\%$$

Substituting the values:

$$Energy\ Efficiency = 100\% - \frac{2\ visits}{5\ visits} \times 100\%$$

$$Energy\ Efficiency = 60\%$$

Thus, there was a significant 60% improvement in labor efficiency due to fewer visits to the mushroom chamber.

CONCLUSION

In conclusion, this research successfully achieved its objectives, demonstrating the efficacy of integrating Fuzzy Logic with IoT technologies to enhance the productivity and efficiency of oyster mushroom cultivation. An Intelligent Assistant System was meticulously developed and deployed within a mushroom cultivation environment through a systematic application of the Waterfall development model. Leveraging IoT for real-time environmental data collection and Fuzzy Logic for sophisticated analysis, the system optimized irrigation schedules based on prevailing conditions.

The quantifiable impact of the intelligent assistant system on oyster mushroom productivity and efficiency was evaluated. Results showed a notable 37.4% increase in total mushroom yield productivity after one month of equipment utilization. Moreover, the system's implementation resulted in a 60% improvement in both time and energy efficiency in maintaining the cultivation environment. This translated to reduced labor and energy expenditure while ensuring consistent and optimal growth conditions for oyster mushrooms.

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