A Dual-Layer Environmental Control Prototype Using ESP32 and SONOFF for Small-Scale Mushroom Farming

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Abstract
This study presents the design and preliminary evaluation of a hybrid IoT-based temperature control system that integrates ESP32 and SONOFF technologies for cloud-enabled environmental regulation in small-scale community mushroom farming. Maintaining stable temperature conditions during the incubation and fruiting phases is critical for optimal yield, yet many rural growers continue to rely on manual misting practices that are labour-intensive and prone to inconsistency. Guided by the Design Thinking framework, the system was developed through iterative, user-centered phases to address the practical challenges of low-connectivity cultivation environments. The ESP32 microcontroller enables real-time local temperature monitoring and manual pump control, while the SONOFF smart switch and THS01 sensor configured via the eWeLink cloud platform support automated misting based on adjustable temperature thresholds. Preliminary testing in a 3×3 m mushroom house under simulated conditions demonstrated that the system maintained target temperature ranges for over 85% of operational time, reducing daily fluctuations from above 6 °C to within ±2 °C. Farmers involved in system demonstrations reported improved environmental control, reduced manual workload, and increased confidence in the cultivation process. The dual-mode architecture, combining offline and cloud-based automation, offers a robust and scalable model suitable for resource-limited farming contexts. This integration of low-cost, accessible IoT components has the potential to digitally empower smallholder growers, promote sustainable smart agriculture, and support digital transformation in rural TVET ecosystems.

Keywords: ESP32, IoT, mushroom farming, smart agriculture, SONOFF.

1.0 Introduction
Mushroom cultivation has emerged as an increasingly viable component of sustainable agriculture, particularly among small-scale growers in rural and semi-urban areas (Mondal, 2025; Sadiq et al., 2024). It offers high nutritional value, minimal land requirements, and relatively low production costs,

making it accessible to community-level farmers seeking alternative or supplementary income streams. However, the success of mushroom production depends heavily on maintaining stable temperature and humidity across two distinct growth phases: incubation, when mycelium colonization occurs, and fruiting, when mushrooms are formed. Each phase demands specific thresholds to ensure healthy growth and maximize yield (Rukhiran et al., 2023). In practice, many small-scale farmers rely on manual misting using spray devices, timers, or personal judgment. While inexpensive, this approach is time-consuming, inconsistent, and vulnerable to human error, particularly under fluctuating weather conditions. These inefficiencies often result in unstable yields, poor crop quality, and increased labour, highlighting the need for more precise and efficient solutions.

Recent advances in smart farming and the Internet of Things (IoT) have demonstrated significant potential for environmental monitoring and control (Amin et al., 2021; Chong et al., 2023; Prashant et al., 2024). Automated systems are increasingly applied in mainstream agriculture to improve stability, efficiency, and productivity. Yet, their adoption in mushroom cultivation remains limited due to several constraints. Many existing solutions are cost-prohibitive for smallholder farmers, depend heavily on stable internet connectivity, or are restricted to monitoring only functions without automated actuation (Elewi et al., 2024). Moreover, most research in IoT based agriculture has focused on general crop systems rather than addressing the specific requirements of mushrooms across incubation and fruiting (Bao, 2020; Eben et.al, 2023; Bujal et.al, 2024). Few systems integrate actuators such as misting pumps that respond automatically to real-time conditions (Irwanto et al., 2024; Kavaliauskas et al., 2022). This gap leaves community level mushroom growers underserved by digital technologies, despite the potential of IoT to improve yield stability and reduce labour requirements.

To address these limitations, this study proposes the design and development of a low-cost, dual-layered environmental control prototype tailored to mushroom cultivation. The system integrates ESP32 and SONOFF smart devices in a hybrid configuration that combines both offline and online functionalities. The ESP32 microcontroller provides local real-time temperature display and manual relay-based override, enabling farmers to maintain control even in low-connectivity environments. Meanwhile, SONOFF smart switches, connected to the eWeLink cloud platform, automate misting based on configurable temperature thresholds for greater consistency. Unlike previous approaches, this dual-mode design ensures reliable operation under rural conditions while remaining affordable and user-friendly. The specific objectives of the study are fourfold: to identify the optimal temperature ranges required during incubation and fruiting, to develop an ESP32-based monitoring system with local display and manual control, to integrate SONOFF devices for cloud-enabled automation, and to evaluate the performance, reliability, and usability of the hybrid prototype. Collectively, these objectives aim to demonstrate how accessible IoT solutions can strengthen small-scale mushroom farming while supporting sustainable smart agriculture.

2.0 Methodology

This study employed the Design Thinking model as a human centered and iterative approach to guide the design and development of a smart temperature control system for mushroom cultivation. The Design Thinking framework, comprising five phases: empathize, define, ideate, prototype, and test was selected to ensure the solution responds effectively to the practical needs and constraints of small scale community mushroom farmers. This approach encourages innovation by deeply understanding user contexts, enabling the co-creation of solutions that are not only technically feasible but also desirable and viable for real-world deployment (Roberto et al., 2021).

2.1 Empathize: Understanding User Needs

In the initial phase, a series of informal interviews and field observations were conducted involving five local mushroom growers operating small sized cultivation houses. The objective was to understand the growers' pain points and current practices in managing temperature, particularly across the two primary growth phases incubation and fruiting. The findings revealed that most farmers relied on manual misting practices to reduce temperature, which led to inconsistent results, labour inefficiencies, and exposure to human error. Additionally, many growers expressed the need for a system that could function in low connectivity environments, be cost effective, and require minimal maintenance.

2.2 Define: Problem Statement

Based on the data collected during the empathize phase, the core problem was defined as follows:

Community mushroom growers lack an accessible and automated system to maintain optimal temperature conditions throughout the cultivation cycle, particularly during incubation and fruiting phases, resulting in unstable yields and increased manual workload.

This definition guided the development of a technological solution tailored to the real constraints and operational practices of rural farming environments.

2.3 Ideate: Conceptualizing the System

In the ideation phase, several system configurations were explored and compared in terms of feasibility, affordability, scalability, and suitability for small-scale mushroom farming. After evaluation, the most promising approach was a hybrid Internet of Things (IoT) architecture that integrates both local and cloud-based functions. This design was chosen because it balances cost-effectiveness, simplicity, and flexibility, making it practical for farmers in semi-rural and low-connectivity environments. The ESP32 microcontroller was selected as the local control unit due to its low price, reliable performance, and wide developer support. Connected to an OLED display, it receives real-time data from the SONOFF THS01 sensor and presents readings on-site, allowing farmers to monitor environmental conditions without internet access. ESP32 also supports a local relay, enabling manual pump activation when the network is unavailable or when direct user intervention is required.

For cloud-based automation, the SONOFF Basic R2 smart switch was integrated with the eWeLink platform to control the misting pump. Through the mobile application, farmers can configure temperature thresholds that align with the needs of each growth phase. Higher temperature and humidity are maintained during incubation to promote mycelial colonization, while cooler and more humid conditions are applied during fruiting to stimulate mushroom body formation. The SONOFF system offers ease of use, affordability, and robust cloud connectivity, complementing the offline functions of the ESP32. By combining these two layers, the framework ensures continuous operation, even under unstable internet conditions, while also providing flexible automation. The conceptual framework of this hybrid IoT solution is illustrated in Figure 1, which highlights the integration of offline monitoring and cloud-enabled control for sustainable mushroom cultivation.

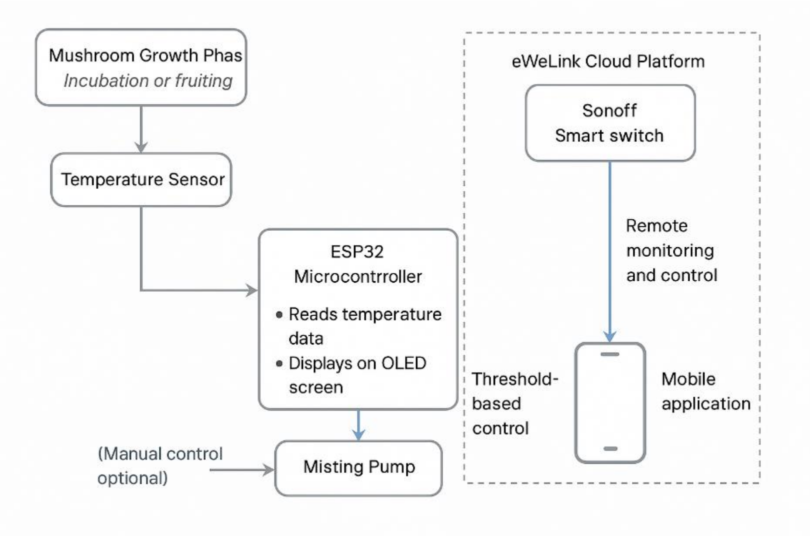

Figure 1: Conceptual framework diagram

2.4 Prototype: System Development

The functional prototype developed in this study integrated both hardware and cloud based components to regulate the internal temperature and humidity of a mushroom cultivation house with minimal manual intervention. At the core of the system was a SONOFF Basic R2 smart switch, connected to a SONOFF THS01 temperature and humidity sensor, enabling real time environmental monitoring and automated misting control through the eWeLink cloud platform. The switch was linked to a misting pump that dispersed a fine water based spray to lower ambient temperature and elevate humidity when needed. Complementing this cloud based control, an ESP32 microcontroller equipped with an OLED display programmed via the Arduino IDE served as a local interface, providing onsite environmental feedback to farmers without requiring internet access. The overall architecture of the system is illustrated in Figure 2.

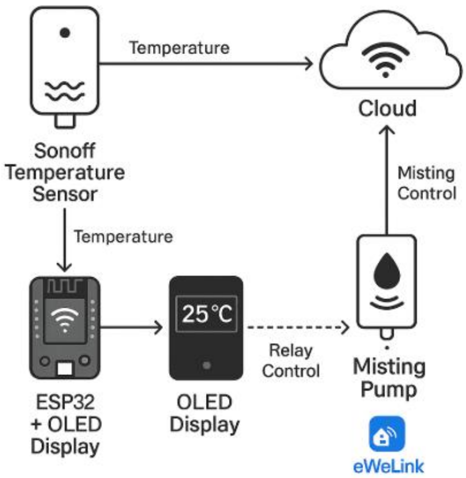

Figure 2: System architecture diagram illustrating the integration of SONOFF temperature sensor, ESP32 display module, and misting pump controlled via the eWeLink cloud platform

2.5 Test: Field Deployment and Evaluation

To evaluate the system's functionality and practicality, the complete prototype was deployed in a 3×3 meter mushroom house over the course of two full cultivation cycles. Prior to deployment, farmers were briefed on how to operate the system, including how to adjust the temperature thresholds in the eWeLink mobile application according to the current mushroom growth phase. Throughout the testing period, data on temperature readings, misting pump activation patterns, and system responsiveness were continuously logged and monitored. Qualitative feedback was also gathered from participating growers through observation and informal interviews to assess usability and acceptance. Farmers reported improvements in consistency of environmental control, reductions in manual labour, and increased convenience in managing the cultivation process. The testing phase not only confirmed the technical performance of the system but also provided insights into its real world applicability, scalability, and potential for broader adoption in similar community farming contexts.

3.0 Results and Discussion

Building upon the system design and implementation processes detailed in Section 2.0, the following results present both technical outcomes and user centred observations gathered during prototyping and deployment phases. Results are discussed in terms of temperature suitability, system functionality, automation efficiency, and end user applicability within small scale mushroom cultivation environments.

3.1 Identification of Optimal Temperature Ranges for Mushroom Growth

Mushroom cultivation involves two critical phases incubation and fruiting each requires distinct environmental conditions. Based on cultivation guidelines (Hakim et al., 2022; Wahab et al., 2019), the incubation phase typically demands higher humidity levels (≥ 85%) and stable temperatures ranging from 22 °C to 26 °C, while the fruiting phase prefers cooler temperatures (18 °C to 22 °C) and even higher humidity (≥ 90% RH). To implement these conditions, the system employed hysteresis control, a method that introduces buffer margins between the activation and deactivation points to reduce frequent switching and protect hardware components. Table 1 details the temperature ON/OFF thresholds used for each growth phase.

The misting system, while primarily temperature-driven, indirectly supported humidity regulation by releasing fine water spray during each cycle. Humidity readings from the SONOFF THS01 sensor were used to validate those levels remaining within acceptable ranges during testing. This strategy proved effective in the field: environmental logging during deployment showed that the system maintained internal temperatures within the desired range for over 85% of the time, with fluctuations reduced from over 6 °C daily (manual system) to within 2 °C post-deployment.

Table 1: Misting temperature thresholds with hysteresis margin

Growth Phase	Misting ON Threshold	Misting OFF Threshold	Target Temperature Range	Humidity Requirement
Incubation	> 26 °C	< 23 °C	22 °C – 26 °C	≥ 85% RH
Fruiting	> 24 °C	< 20 °C	18 °C – 22 °C	≥ 90% RH

3.2 Development of Real Time Temperature Monitoring Prototype

Using ESP32

To fulfil the second objective of this study, a real-time temperature monitoring system was successfully designed and implemented using the ESP32 microcontroller, supported by an OLED display module and a relay-based control mechanism. The ESP32 was programmed via the Arduino IDE to read temperature data from the SONOFF THS01 sensor and to display the readings locally on a compact OLED screen. This enabled continuous environmental monitoring without relying on cloud connectivity, allowing mushroom growers to visually observe temperature changes on site. The use of ESP32 was selected due to its built-in Wi-Fi capability, low power consumption, and proven suitability for smart farming systems (Hercog et al., 2023).

In addition to passive monitoring, the ESP32 module was integrated with a manual override mechanism through a relay module, which controlled the activation of the misting pump. This feature allowed users to manually trigger misting during network downtime or in cases requiring immediate intervention. During initial system testing and demonstration sessions, the ESP32 consistently captured and displayed temperature readings at one-second intervals without functional interruption. Although full field deployment and long-term performance logging are yet to be conducted, early testing indicates that the system responds in real-time and offers stable visual output under standard operational conditions.

Preliminary user feedback gathered through informal demonstrations was positive. One grower remarked, *"With the display in front of me, I no longer need to guess. I can see exactly when the temperature rises and act immediately."* Another commented, *"The manual button is a great backup when I feel the air is too warm, especially when the internet lags."* These initial reactions suggest that the system has the potential to improve user confidence and decision-making in environmental control.

The dual-functionality real-time monitoring and local actuation was particularly appreciated in low-connectivity settings and is expected to increase resilience and usability once field trials are formally carried out in the next phase of the study.

3.3 Integration of SONOFF Smart Switches and eWeLink for Automated Misting

To achieve the third objective, the SONOFF Basic R2 smart switch was successfully integrated with the SONOFF THS01 temperature sensor and the eWeLink cloud platform to enable automated misting control based on pre-set temperature thresholds. The THS01 sensor continuously measured environmental temperature inside the mushroom house and relayed the data to the eWeLink mobile application via Wi-Fi connectivity. Through this application, users were able to configure automation rules, including specific temperature values to activate or deactivate the misting pump according to the requirements of each growth phase.

Initial testing during controlled simulations confirmed that the system responded accurately to the defined temperature rules. When the ambient temperature exceeded the upper threshold (e.g., 26 °C for the incubation phase), the cloud-triggered automation successfully activated the misting pump. Likewise, once the temperature dropped below the lower threshold (e.g., 23 °C), the misting pump was automatically turned off, demonstrating effective hysteresis control. These automations were executed without user intervention, verifying the functionality and responsiveness of the cloud-based logic (Vădan & Miclea, 2024).

One of the key advantages observed was the remote configurability of the system. Farmers were able to adjust the misting control parameters through the eWeLink app without needing to access or reprogram the hardware physically. This flexibility improved overall system usability, particularly in remote or semi-automated cultivation setups. Preliminary user feedback gathered through demonstration sessions was positive. One participant remarked, *"Now I can update the temperature settings even when I'm not near the farm. I just use my phone."* These early reactions suggest that the system has the potential to reduce manual workload and enhance environmental consistency in small-scale mushroom operations.
While these findings are based on early-stage testing, they provide foundational insights for future large-scale deployments and the integration of cloud-based environmental automation in resource-limited agricultural settings.

3.4 Preliminary Assessment of System Performance, Reliability, and Usability

To address the fourth objective, preliminary testing was conducted to assess the performance, reliability, and user-friendliness of the integrated temperature and humidity control system under simulated mushroom farming conditions. The system was tested in a 3 × 3 meter cultivation setup over a simulated two-phase cycle to observe its ability to maintain target environmental conditions and meet the practical operational needs of small-scale mushroom farmers. Although long-term field deployment has not yet been conducted, early testing demonstrated that the system was able to respond to environmental changes in real time, with misting activation occurring in accordance with predefined thresholds.

A graphical comparison of daily temperature fluctuations before and after automation is presented in Figure 3. Under manual control, temperatures varied sharply between 25–29 °C, with sudden drops during misting events, resulting in fluctuations exceeding 4–6 °C per day. In contrast, the automated system maintained a narrower band of 23.5–25 °C, effectively reducing fluctuations to within ±1–2 °C. This stability is particularly important for mushroom production, as consistent thermal conditions reduce stress on the mycelium and promote uniform growth.

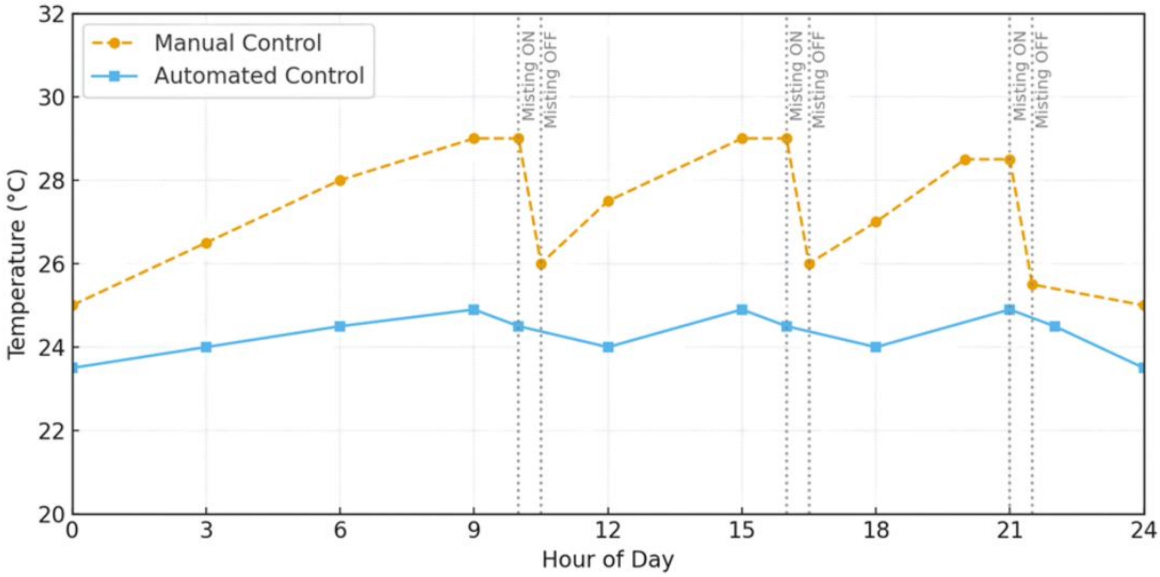

Figure 3: Temperature comparison between manual and automated control systems with misting ON/OFF thresholds

Similarly, humidity regulation showed significant improvements (Figure 4). The manual system produced drastic swings, with relative humidity ranging from 70% to 98%, reflecting abrupt spikes after misting and steep declines thereafter. The automated system, however, sustained humidity within 85–92%, using a hysteresis-based strategy that activated misting below 85% and deactivated it above 92%. This tighter regulation not only aligns with the recommended cultivation requirements (>85% RH) but also minimizes the risk of contamination associated with unstable humidity.

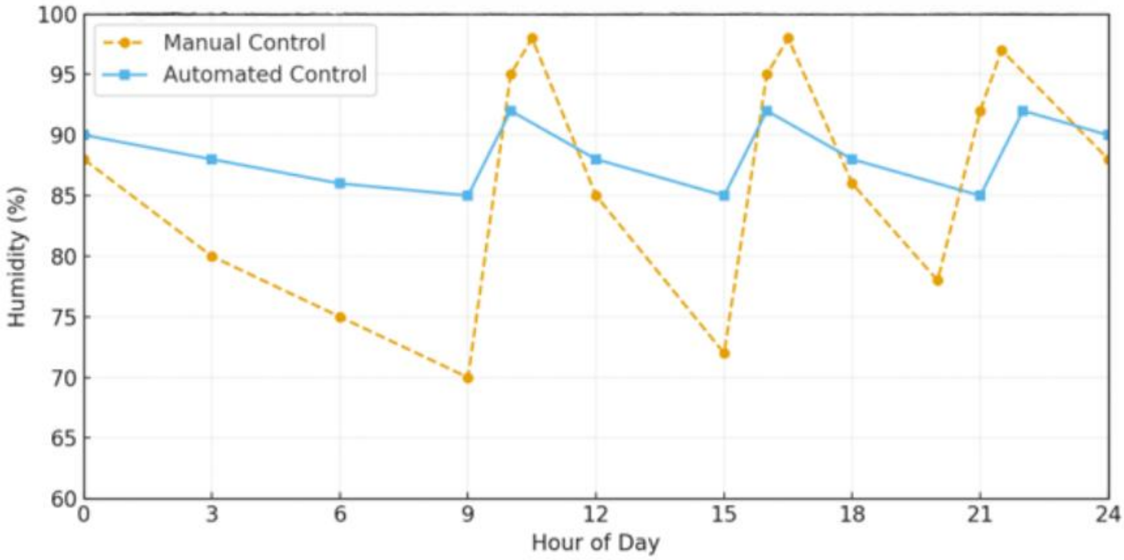

Figure 4: Humidity comparison between manual and automated control systems with misting ON/OFF thresholds

These findings align with previous literature that highlights the critical role of environmental stability in mushroom yield optimization. Automated environmental systems that maintain narrow temperature and humidity bands have been shown to improve mycelial development and fruiting consistency, particularly in high-humidity crops such as mushrooms (Triandini et al., 2024).

Early feedback from growers who observed system demonstrations was encouraging. One participant shared: "*Before this system, I had to manually spray water every few hours, but now I can monitor and control it through my phone*." This reflects the perceived value of automation and visual feedback for reducing manual labour and increasing environmental awareness. The hybrid architecture combining SONOFF-based cloud automation and ESP32-based local control was positively received, particularly for its offline fallback mechanism. Users expressed confidence in having manual override options when internet connectivity was limited. While minor misting delays (3–5 seconds) were noted during cloud-based triggers, these were not expected to significantly affect environmental control under actual farming conditions.

In summary, although full-scale deployment is planned for future phases, initial assessments suggest that the integrated system holds strong potential to support the operational requirements of small-scale mushroom growers. By maintaining both temperature and humidity within narrow optimal ranges, the system demonstrates reliable, user-friendly, and cost-effective environmental control that can enhance productivity in tropical climates such as Malaysia.

4.0 Conclusions

This study presented the development and preliminary evaluation of a dual-layered IoT-based temperature control prototype tailored for small-scale mushroom cultivation. The system integrates an ESP32 microcontroller for real-time local temperature display and manual control, alongside a SONOFF smart switch and temperature sensor configured via the eWeLink cloud platform to enable automated misting activation based on configurable thresholds. The system architecture was guided by the Design Thinking framework to ensure responsiveness to end-user needs in low-connectivity and resource-limited farming environments.

Four main objectives were addressed. Firstly, temperature requirements for incubation (22–26 °C) and fruiting (18–22 °C) phases were identified based on established best practices in mushroom farming. Secondly, a functional ESP32-based module was designed and implemented to provide continuous on-site temperature monitoring with relay-based manual control. Thirdly, the SONOFF THS01 and Basic R2 devices were successfully integrated with the eWeLink cloud platform to automate misting operations through user-defined temperature thresholds. Finally, preliminary testing and simulated deployment showed that the system could reduce temperature fluctuations from over 6 °C daily (manual method) to within ±2 °C, while maintaining usability and reliability. Early user feedback also indicated improved confidence, reduced labour, and increased perceived control through the hybrid interface.

These findings suggest that the proposed system holds significant promise as a low-cost, adaptable, and user-friendly solution for precision environmental control in community mushroom farming. Its dual-mode operation cloud-based automation with offline fallback ensures operational continuity and aligns well with the realities of rural digital infrastructure. Furthermore, the system's simplicity and affordability make it highly suitable for integration into vocational education and training (TVET) programmes, where it can serve as a practical tool for hands-on learning in IoT applications for agriculture.

Despite its contributions, this study is subject to several limitations. First, the evaluation was restricted to prototype development and preliminary simulations within a small-scale setup; full-scale field deployment across multiple cultivation cycles was not conducted. Second, the system primarily focused on temperature regulation, while the SONOFF sensor's full humidity-control capabilities were not fully integrated or validated. Third, long-term performance tracking was not carried out, limiting insights into the durability and stability of the system in real farming conditions. Finally, the study did not include direct measurements of mushroom yield outcomes, which are critical for assessing agricultural impact.

Future research should build on these preliminary findings by conducting

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extended field trials across multiple cultivation cycles to validate system robustness and assess its impact on mushroom yield. Integration of real-time humidity control, in addition to temperature regulation, is recommended to achieve a fully optimized microclimate management system. Continuous data logging via platforms such as MQTT or Blynk should be implemented to enhance monitoring, analytics, and decision support. Sustainability could be further strengthened through solar-powered operation to support off-grid adoption. Finally, integration into TVET curricula should be expanded, allowing the system to serve both as a training tool for digital agriculture and as a scalable model for community-based smart farming.

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Author Contributions
A. Mohd Hafiez: Conceptualisation, Data Collection, Data Curation, Validation; **R. Sharifah Nadiyah:** Conceptualisation, Writing, Validation, Supervision. **A.R. Rahaliza:** Data Collection, Data Curation; **B. Haslizah:** Reviewing and Editing.

Conflicts of Interest
The manuscript has not been published elsewhere and is not under consideration by other journals. All authors have approved the review, agree with its Submission and declare no conflict of interest in the manuscript.

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