Jurnal Personalia Pelajar 28(1): 447-466
https://doi.org/10.17576/personalia.2801.2025.42
ISSN 0128-2735

Smart Mushroom House System (SMUSH) for Economical Cultivation of Wood Ear Mushroom, Oyster Mushrooms and Milky Mushroom

(Rumah Cendawan Pintar (SMUSH) untuk Penanaman Cendawan Telinga Kera, Cendawan Tiram dan Cendawan Melati)

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ABSTRACT

A mushroom house is a structure specifically designed to provide the necessary environmental conditions for cultivating mushrooms. To build a semi-automated Smart Mushroom House System (SMUSH), a fragmented Internet of Things (IoT) system with sensor devices was applied. This existing technique is designed specifically for warm-temperature (>20°C) and wide-range (5–35°C) mushroom strains such as Auricularia cornea, Pleurotus djamor, Pleurotus citrinopileatus, Pleurotus pulmonarius, and Calocybe indica. Key parameters monitored include temperature and relative humidity. The system maintained daily temperature and humidity levels mostly between 26.4°C and 27.0°C and 88.1% and 93.1%, respectively. To evaluate contamination rates due to pests, twenty Wood Ear mushroom bags were adopted. Ten were incubated in a mushroom farm in Serdang (LCS) and ten in SMUSH. To assess the compatibility of Oyster and Milky mushrooms within SMUSH, we recorded the growth duration from the full colonization stage until harvest and compared it with the optimal growth period. All mushrooms were successfully harvested within the optimal timeframe, demonstrating good growth performance and confirming SMUSH's effectiveness. The result shows that the low-cost smart mushroom house, SMUSH, successfully met the environmental requirements for the growth of Wood Ear, Oyster, and Milky mushrooms. With an initial cost of RM780 (180 USD), SMUSH can accommodate 40–50 mushroom bags at a time. Consequently, SMUSH has achieved Technology Readiness Level 4 (TRL 4) in the Technology Readiness Level system. The innovation of SMUSH fosters student entrepreneurship by promoting critical thinking, problem-solving, and hands-on involvement in sustainable agribusiness challenges.

Keywords: Wood ear, oyster, milky, smart mushroom house, Internet of Things

ABSTRAK

Rumah cendawan ialah struktur yang direka khas untuk menyediakan keadaan persekitaran yang diperlukan bagi penghasilan cendawan. Bagi membina Sistem Rumah Cendawan Pintar (SMUSH) yang separa automatik, sistem "Fragmented Internet of Things (IoT)" bersama peranti-peranti sensor telah diaplikasikan. Teknik ini dikhususkan untuk strain cendawan yang bersuhu suam (>20°C) dan bersuhu dalam lingkungan luas (5–35°C) seperti cendawan Auricularia cornea, Pleurotus djamor, Pleurotus citrinopileatus, Pleurotus pulmonarius dan Calocybe indica. Suhu dan kelembapan adalah antara parameter yang dipantau. Sistem yang mengawal suhu harian dan kelembapan relatif (%RH) yang direka ini berjaya dikekalkan majoriti antara 26.4°C hingga 27.0°C dan 88.1% hingga 93.1%. Untuk menguji peratusan pencemaran oleh serangga perosak, dua puluh beg cendawan Telinga Kera digunakan untuk membandingkan keberkesanan SMUSH; sepuluh diinkubasi di ladang cendawan di Serdang (LCS) dan sepuluh di SMUSH. Bagi menguji keserasian cendawan Tiram dan cendawan Melati di dalam SMUSH, kami merekodkan tempoh pertumbuhan dari peringkat kolonisasi penuh hingga matang untuk dituai, dan membandingkannya dengan jangka masa pertumbuhan yang optimum. Kesemua cendawan berjaya dituai dalam tempoh optimum menunjukkan kadar pertumbuhan yang baik, dengan itu membuktikan keberkesanan SMUSH. Kajian ini menunjukkan bahawa rumah cendawan pintar kos rendah, SMUSH, berjaya memenuhi keperluan persekitaran untuk pertumbuhan cendawan Telinga Kera, Tiram, dan Melati. Dengan kos permulaan hanya RM780 (180 USD), SMUSH mampu menampung 40-50 beg cendawan pada satu masa. Oleh itu, SMUSH telah mencapai taraf TRL 4 dalam sistem Tahap Kesediaan Teknologi. Inovasi SMUSH menggalakkan keusahawanan pelajar dengan memupuk pemikiran kritikal, kemahiran menyelesaikan masalah, dan penglibatan secara praktikal dalam cabaran perusahaan agrikultur lestari.

Kata kunci: Telinga kera, tiram, melati, rumah cendawan pintar, Internet of Things

INTRODUCTION

A mushroom house, also known as a mushroom chamber or mushroom farm, is a structure specifically designed to provide the necessary environmental conditions for cultivating mushrooms. Smart mushroom houses are a recent development in mushroom cultivation, incorporating advanced technologies to improve efficiency and productivity (Aggarwal & Singh, 2022). Smart mushroom houses today mostly utilize the Internet of Things (IoT) or Wireless Sensor Network (WSN).

The core of the automated system, employing IoT technology, relies on an IoT Wireless Fidelity (Wi-Fi) module device. This device functions as a sensor node, collecting environmental data and transmitting it to the Internet for monitoring and analysis. Additionally, the IoT device acts as a controller, ensuring the maintenance of environmental conditions at the desired levels. The internal control system of the device activates automatically when the environmental conditions deviate from the optimal state. However, a consistent Internet connection is necessary for this system to ensure the transmission of data to the online platform. Powered by a battery, IoT Wi-Fi module devices can operate for several months (Mahmud et al., 2018).

The smart house developed by Mahmud et al. (2018) presents a fully automatic centralized ecosystem of IoT devices designed to collaborate and offer remote control options. In contrast, this project proposes a semi-automatic system with multiple fragmented IoT devices functioning as sensors to monitor mushroom growth. It is considered semi-automatic due to its ability to detect suboptimal parameters but requires human interference in adjusting the humidifier level upon receiving notification and refilling the water tank. In contrast, a fully automated system can detect and act upon it to optimize the condition on the spot.

The decision to avoid centralizing the ecosystem in this project is driven by cost, knowledge, and adaptation barriers. By employing distinct IoT devices that work autonomously, it becomes substantially simpler to comprehend the specific functionality of each device and adapt it to a mushroom house system. Hence, this approach aims to streamline device implementation for our target users, particularly small-scale mushroom farmers.

The implementation of IoT solutions can incur high initial setup and infrastructure costs (Bunluewong & Surinta, 2021). The centralization of the IoT ecosystem necessitates the purchase of a specific set of devices compatible with each other, resulting in less flexibility. Additionally, it requires hiring a programmer to integrate various applications into a unified platform, along with ongoing maintenance costs for the platform domain. In contrast, a fragmented setup proves to be a potentially more cost-effective alternative, especially for smaller-scale operations, while maintaining full functionality with occasional manpower support. A simpler fragmented IoT system is preferred when complexity is unnecessary for the desired level of control.

For smaller-scale mushroom cultivation operations, a fragmented IoT system setup offers scalability and ease of expansion without requiring a huge investment in centralized IoT infrastructure. Moreover, a fragmented IoT system, being simpler to operate and maintain, is more accessible to individuals with limited technical expertise compared to an integrated and centralized IoT system, which may demand specialized knowledge for setup and troubleshooting. A fragmented IoT system approach allows for more manual control and customization, aligning with specific preferences in the mushroom cultivation process, while integrated IoT solutions may come with predefined features that might not perfectly match unique conditions. Despite the benefits of a centralized IoT system, resistance to adopting complex IoT also arises from concerns about data security, privacy, or simply a lack of understanding among individuals and organizations (Kim & Park, 2020).

In a common basic smart mushroom house, real-time data of parameters are temperature, humidity, and CO_2 concentration. As the technologies are still growing, sensors for more specific parameters such as light intensity have also been included (Chen et al., 2022). In this study, the SMUSH system employs a fragmented IoT technology to monitor primarily vital parameters like temperature, humidity, and light exposure.

Integrated IoT System

Integrated IoT involves IoT technologies into various systems or environments to enhance connectivity, automation, and data exchange capabilities. In the context of smart mushroom houses, integrated IoT is essential for optimizing the cultivation process by enabling real-time monitoring, control, and automation of environmental parameters such as temperature, humidity, and ventilation (Dipali et al., 2023).

Integrated IoT with a centralized app involves a system where IoT devices are interconnected and communicate through a centralized platform or application. The centralized app acts as a hub for managing interactions between IoT devices, allowing users to monitor, control, and automate connected devices easily from a single interface (Kang et al., 2022; Wang et al., 2019).

Fragmented IoT System

Non-integrated or fragmented IoT systems refer to an IoT ecosystem where devices, systems, or platforms lack seamless integration and interoperability. Fragmented IoT systems can offer several advantages, including the flexibility to use diverse IoT devices from different manufacturers or with varying protocols, allowing for a wider range of options and customization. This flexibility is beneficial in environments where specific devices are preferred for their unique features or functionalities. Additionally, fragmented IoT setups provide autonomy to individual devices, enabling them to function independently without relying on a centralized system. This independence is advantageous in scenarios where connectivity to a central network is intermittent or unreliable (Yousefpour et al., 2019).

Another benefit is enhanced security and privacy; independent operation reduces exposure to vulnerabilities associated with centralized systems (Overmars & Venkatraman, 2020; Baucas et al., 2023). Moreover, non-integrated IoT systems offer scalability and cost-effectiveness by allowing incremental deployment of devices without immediate integration into a unified network, which is useful in scenarios with budget constraints or resource limitations (Tyler et al., 2022; Tyrovolas et al., 2022). Furthermore, the capability of fragmented IoT systems to function independently and allow for individual device servicing without impacting the entire system in the event of a device failure is recognized as a practical benefit.

Ultimately, although a fragmented IoT system requires multiple applications to monitor various parameters in comparison to one centralized app, fragmentation offers flexibility, autonomy, security, and scalability benefits, along with easier individual maintenance. These advantages are beneficial especially for users with limited technological proficiency.

OBJECTIVES

To design a semi-automatic smart mushroom house (SMUSH) that meets the optimal conditions for the growth of warm (greater than 20°C) and wide-range (5–35°C) mushroom strains.

METHODOLOGY

Growth Parameters of Mushrooms Grown in SMUSH

The SMUSH system requires monitoring and adjustment of growth parameters, tailored to meet the specific range of environmental needs for the five chosen mushroom species. The existing setting is specialized for warm (>20°C) and wide-range (5–35°C) mushroom strains. These parameters are detailed and summarized in Table 1 through Table 5.

TABLE 1. Growth Parameters of Wood Ear mushroom Auricularia cornea (Stamets, 2000)

Parameters Stage of Growth	Spawn Run	Primordia Formation	Fruiting Body Development
Temperature (°C)	24–30°C	12–20°C	21–30°C
Relative Humidity (%)	90-95%	90-100%	85-90%
Light Requirements	Not needed	500-1000 lux	500-1000 lux
Duration	25-40 days	5-10 days	5-7 days

TABLE 2. Growth Parameters of Pink Oyster mushroom Pleurotus djamor (Stamets, 2000)

Parameters Stage of Growth	Spawn Run	Primordia Formation	Fruiting Body Development
Temperature (°C)	24–30°C	18–25°C	20–30°C
Relative Humidity (%)	90-95%	95-100%	85-90%
Light Requirements	Not needed	750-1500 lux	750-1500 lux
Duration	7-10 days	2-4 days	3-5 days

TABLE 3. Growth Parameters of Yellow Oyster mushroom *Pleurotus citrinopileatus* (Stamets, 2000)

Parameters Stage of Growth	Spawn Run	Primordia Formation	Fruiting Body Development
Temperature (°C)	24–29°C	21–32°C	20–29°C
Relative Humidity (%)	90-100%	98-100%	90-95%
Light Requirements	Not needed	500-1000 lux	500-1000 lux
Duration	10-14 days	3-5 days	3-5 days

TABLE 4. Growth Parameters of Grey Oyster *Pleurotus pulmonarius* (Stamets, 2000)

Parameters Stage of Growth	Spawn Run	Primordia Formation	Fruiting Body Development
Temperature (°C)	24–29°C	21–32°C	18–24°C
Relative Humidity (%)	90-100%	98-100%	90-95%
Light Requirements	Not needed	500-1000 lux	500-1000 lux
Duration	10-14 days	3-5 days	3-5 days

TABLE 5. Growth Parameters of Milky mushroom *Calocybe indica* (Subbiah & Balan, 2015; Milky Mushroom (*Calocybe Indica*) | ICAR-Indian Institute of Horticultural Research, n.d.; S. Maheswari & R. Chithiraichelvan, 2018; Nath et al., 2023; Sornprasert et al., 2022)

Parameters Stage of Growth	Spawn Run	Primordia Formation	Fruiting Body Development
Temperature (°C)	30-35°C	30-35°C	30–38°C
Relative Humidity (%)	80-85%	80-85%	85-90%
Light Requirements	Not needed	500-1000 lux	1600 lux
Duration	21-28 days	10-20 days	3-7 days

Development of SMUSH

SMUSH was located and installed in front of the Functional Omics and Bioprocess Development Laboratory at the Institute of Biological Sciences, Faculty of Science, Universiti Malaya, Kuala Lumpur, Malaysia (OMICS LAB). This site was selected due to its protection from direct sunlight, as exposure to direct sunlight is detrimental to mushrooms, as noted by Sharma et al. (2007). The area was cleaned with a wet cloth rag, sanitized with 75% ethanol, followed by Nippon Paint Weatherbond Exterior paint. The selection of this particular product was based on its commendable anti-fungal properties, making it an optimal choice for the SMUSH area to avoid growth of unwanted wall moulds. Notably, Nippon Paint promises at least 7 years of protection against fungus, algae, flaking, and efflorescence, thereby ensuring enduring performance and dependability, as stated by Nippon Paint Malaysia (2020) in the Weatherbond Technical Data Sheet. Its resistance to fungus is a particularly significant advantage. Given that this experiment deals with fungi, the goal is to minimize the growth of contaminant fungi in the area.

The setup comprised a 143cm (L) x 73cm (W) x 195cm (H) plastic greenhouse with metal racks. Metal racks are preferred over wooden racks to ensure no growth of unwanted fungi on the racks due to the high humidity condition in SMUSH. The arrangement included placement of the smart air humidifier on the floor, an air filter on the rack and an exhaust fan at the top middle of the greenhouse for adequate air ventilation. To enhance accuracy in monitoring environmental conditions, an INKBIRD IBS-TH3 WiFi thermometer and hygrometer was positioned nearby the rack occupied with mushroom bags, acknowledging the potential variability in humidity across different sections of the mushroom house. A CCTV system was strategically set up to observe and record growth, facing only one side

FIGURE 1. Preparation of SMUSH area

FIGURE 2. SMUSH setup

of the mushroom bags, due to the limited availability of one CCTV. Additionally, a 450nm-485nm blue LED strip was positioned along the metal rack to provide appropriate illumination for the mushrooms' growth.

Table 6 outlines the components of the SMUSH system, detailing their respective functions and cost. SMUSH can accommodate 40-50 mushroom bags, providing an efficient setup for small-scale mushroom cultivation, especially for this pilot project. The total cost for all components is RM780 (180 USD).

Blue LED Light Exposure to Wood Ear and Oyster Mushrooms

Mushrooms experience morphological changes depending on exposure to certain light wavelengths (Park & Jang, 2020). According to Ibrahim and Mao (2024), no LED treatment during the mushroom's mycelium colonization stage is needed. LED treatments using blue lights did not affect the mycelium growth positively most probably because no light is required

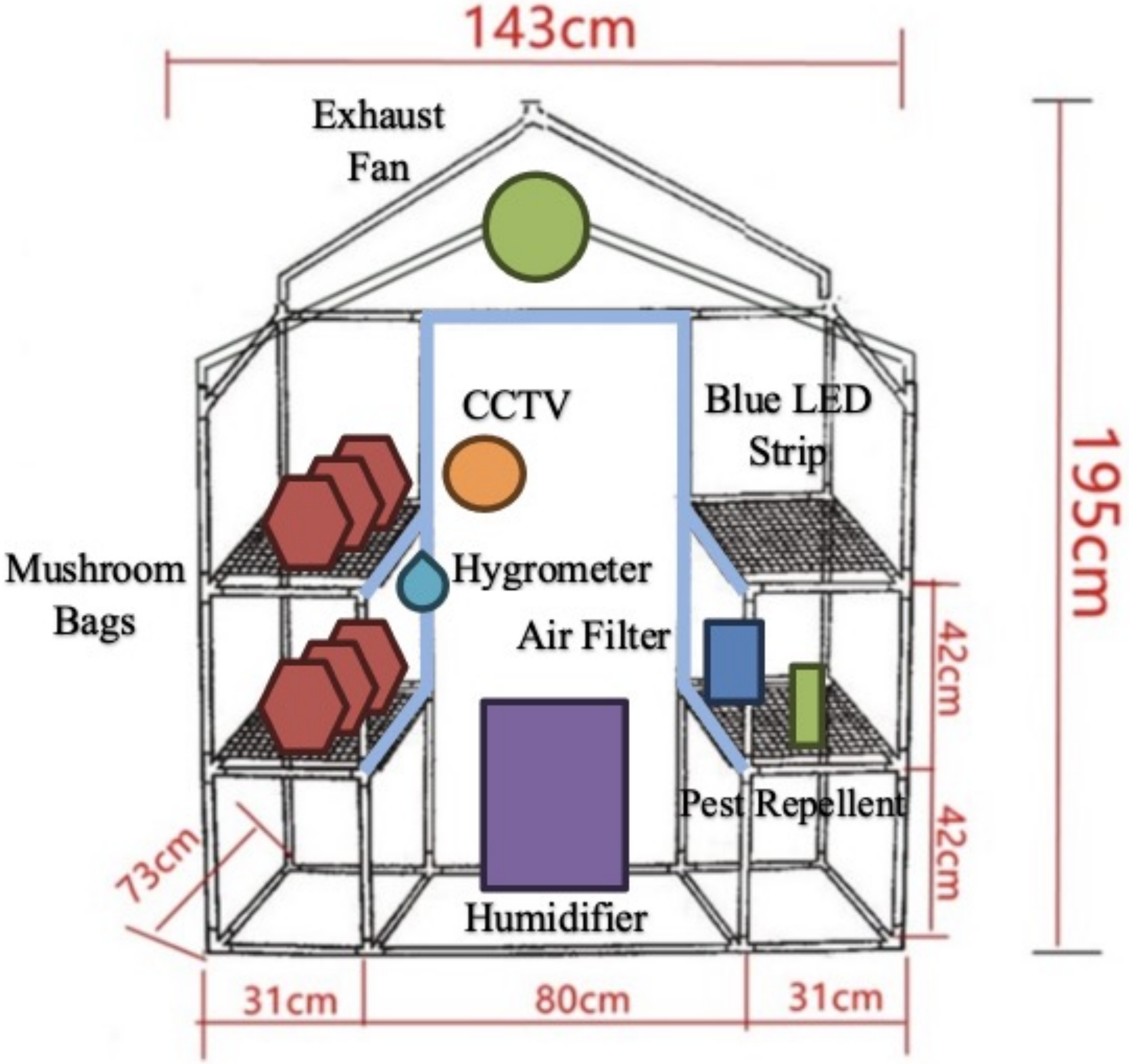


FIGURE 3. SMUSH's interior setup plan

during the mycelium colonization stage of mushrooms, consistent with findings by Stamets (2000). Additional light treatment causes a reduced growth rate of mycelium in the colonization stage (Ibrahim & Mao, 2024). In nature, mycelium usually spreads underground around the root (Pérez-Jiménez, 2006) or is hidden inside opaque substrates like dead woods hence it was usually in darkness.

At the stage of fruiting body formation (reproductive stage), blue LED (475nm) is the optimal treatment for promoting pinhead emergence and fruiting body formation, leading to fast growth and increased yield of fruiting bodies in Wood Ear and Oyster mushrooms (Ibrahim & Mao, 2024). In a study done by Wang et al. (2020), blue light strongly improved the growth rate of all organs, significantly in pileus growth of Oyster mushroom (*Pleurotus pulmonarius*) due to improved glycolysis and the pentose phosphate pathway. Meanwhile, red light slightly inhibited growth of the mushroom cap (pileus). As Wood Ear mushrooms mainly have with short stalks (stipe), theoretically, red light should not be introduced.

Wood Ear Mushroom Growth and Yield Comparison in LCS and SMUSH

To evaluate the effectiveness of SMUSH in terms of managing contamination by pests, 20 fully colonized Wood Ear mushroom bags prepared by LCS were

TABLE 6. List of components in SMUSH with its function and cost price

Item	Function
Plastic PE and PVC Greenhouse (RM180)	A greenhouse acts as an enclosed area that helps maintain consistent internal temperatures by reducing weather-related fluctuations.
Blue LED Strip, 450nm–485nm, 5M, 12V (RM32)	To promote pinhead emergence and fruiting body formation, leading to fast growth in Wood Ear and Oyster mushrooms (Ibrahim & Mao, 2024). The light is switched on the whole period of primordia formation and fruiting body development.
Ventilator / Exhaust Fan (RM31)	To disperse heat by promoting air movement.
Wi-Fi Thermometer Hygrometer Monitor and Data Logger (RM73)	To record temperature and relative humidity. Allows real-time observation through smartphone and sends alerts. Data logger automatically records temperature and relative humidity over time.
Wi-Fi CCTV Camera 1080P (RM79)	To observe real-time recorded mushroom growth.
Smart Humidifier with 16L tank (RM151)	To release fine mist particles by atomization. It can automatically adjust the humidity level as set with a timing function. Able to last at least 3 days between refills.
Air Purifier (RM148)	To ensure air ventilation and filter air to reduce contamination.
Lavender or Peppermint Essential Oil (RM27)	To mask the smell of mushroom substrate thus reduce pest attraction (Erland et al., 2015; Mauchline et al., 2005).
Huntkey SZN-501 Universal Socket Plug (RM59)	To allow for the connection of various electrical devices and equipment in SMUSH.

utilized: 10 were placed in LCS and 10 in SMUSH, allowing for a comparative analysis in terms of contamination rate (%) and flushing rate (%). Fruiting body results were compared in terms of fresh weight and dry weight. The fresh mushrooms were placed in a dehydrator at 60°C for 24 hours before measuring their dry weight (Nadew et al., 2024). To study the cause of differences in the results, a comparison of cultivation area parameters between LCS and SMUSH was also conducted, observing differences in internal and external temperature and relative humidity.

Oyster Mushroom and Milky Mushroom Flushing Test

For the growth of Oyster mushrooms and Milky mushrooms, instead of comparing them with traditional farms, we tested the growth duration from full colonization to harvest to ensure successful flushing within the expected timeframe, as outlined in Tables 2 to 5. If the mushrooms flushed within the specified duration range, it indicates that they were growing at an optimum rate and that SMUSH provided an optimal environment for growth. Three Pink Oyster, three Yellow Oyster, twenty Grey Oyster, and five Milky mushroom bags were placed in SMUSH after full colonization and observed until harvest. The duration was recorded and compared with optimal duration as outlined in Tables 2 to 5.

RESULTS AND DISCUSSION

Features of SMUSH

Figure 4 and Figure 5 depict the exterior and interior of SMUSH with all components assembled. The mist from the humidifier and the blue light illumination are also visible.

FIGURE 4. Exterior of SMUSH

FIGURE 5. Interior of SMUSH

Figure 6 and Figure 7 is a set of data collected over 10 days, where the data logger recorded temperature and relative humidity in SMUSH every 5 minutes. A total of 2880 entries were successfully recorded and summarized into the bar charts.

Based on Figure 6, the mode temperature range of 26.4-27.0°C indicates that SMUSH is suitable for the spawn run and fruiting body development of Wood Ear mushrooms, but not optimal for primordia formation, as SMUSH cannot reach the 12.0-20.0°C range without the use of an air conditioner. Therefore, by accepting this compromise, SMUSH's fiscal sustainability is maintained while guaranteeing the successful execution of its principal purposes.

Based on Figure 7, the mode relative humidity range is 88.1-93.1%, indicating that SMUSH is suitable for all stages of Wood Ear mushroom growth. During this 10-day observation, SMUSH was incubating Wood Ear mushrooms in their primordia formation stage followed by the fruiting body development stage.

Table 7 shows that the maximum temperature inside SMUSH could reach as high as 31.1°C, with a minimum of 25.8°C, an average of 27.5°C, with a standard deviation (SD) of 1.2°C, indicating a relatively narrow variation between daytime and nighttime. Table 7 also shows that the mode temperatures ranged between 26.4°C and 27.0°C, suggesting most temperatures were within this range. The highest relative humidity (%) in SMUSH reached 99.1%, with a minimum of 68.1%, an average of 88.8% (SD of 1.9%), and a mode ranging

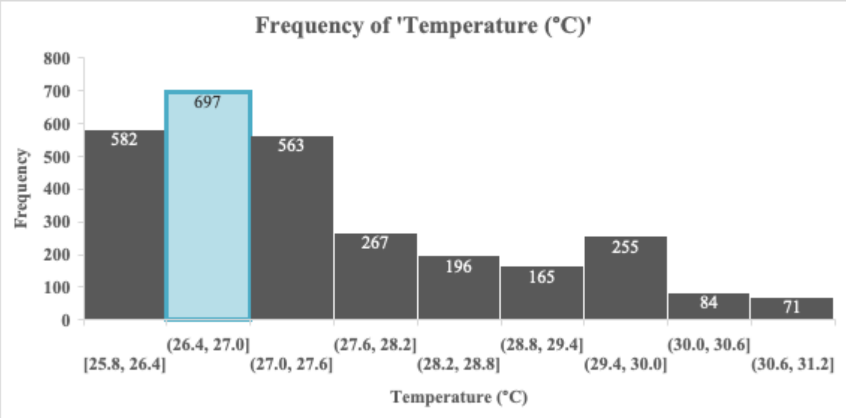


FIGURE 6. Frequency of Temperature (°C) within 2880 entries recorded

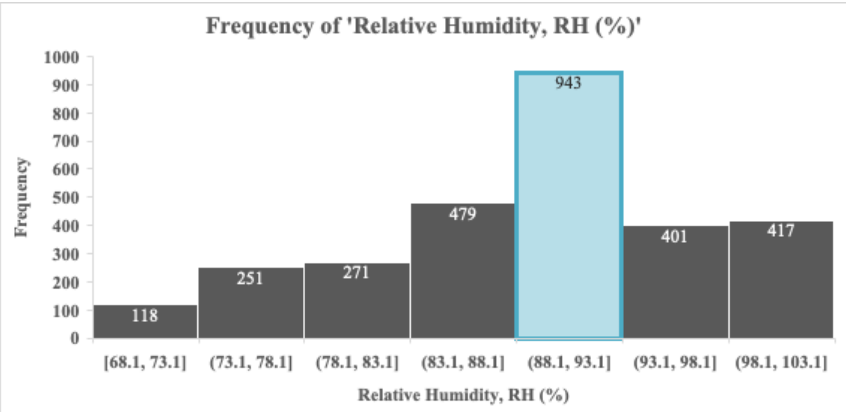


FIGURE 7. Frequency of Relative Humidity, RH (%) within 2880 entries recorded

from 88.1% to 93.1%. This indicates that the humidity levels were generally high with moderate variation, reflecting stable and high humidity conditions.

User Interface of Applications Used for SMUSH Monitoring

The INKBIRD IBS-TH3 Plus, manufactured by INKBIRD Tech. C.L, uses the "INKBIRD" app to monitor temperature and relative humidity. The EZVIZ C1HC 1080P, manufactured by HANGZHOU EZVIZ NETWORK CO. LTD, uses the "EZVIZ" app to observe SMUSH mushrooms in real time. All devices must be connected to Wi-Fi to enable real-time observation via a smartphone.

Figure 8 shows the dashboard in the INKBIRD application where users can know the current temperature and relative humidity in SMUSH. Additionally, notifications will be sent to alert users if the temperature or relative humidity exceeds the user-defined limits. Data collected can be reviewed daily, weekly, monthly, every three months, every six months, or yearly. The system also supports data export in .csv file format.

Figure 9 shows the camera view in the INKBIRD application, where users can monitor real-time conditions in SMUSH. The storage can hold up to 50 days of recordings with a 120GB memory card. The system also supports exporting and sharing playback videos, allowing users to create time-lapse videos of mushroom growth. This camera is particularly useful for users to verify if the humidifier has stopped due to an empty tank or if the light has been switched off.

Feature Comparison Between LCS And SMUSH

Table 8 presents a comparison of features between the LCS and SMUSH systems, highlighting key differences in design and components. A subtle distinction can be observed regarding their sources of humidity. SMUSH utilizes a smart humidifier that releases finer water particles, automatically maintaining humidity levels as configured without excessive wetness. In contrast, LCS employs a timed water sprinkler system that produces larger water particles, leading to large water puddles that can attract flying pests if not promptly removed. Furthermore, this also may contribute to the growth of unwanted moulds as larger water droplets can settle on surfaces and create damp spots.

TABLE 7. Summary of environmental parameters of SMUSH

Parameters	SMUSH
Average Temperature (°C)	27.5°C
Minimum Temperature (°C)	25.8°C
Maximum Temperature (°C)	31.1°C
Mode Temperature (°C)	26.4 - 27.0°C
Standard Deviation of Temperature (°C)	1.2°C
Average Relative Humidity (%)	88.8%
Minimum Relative Humidity (%)	68.1%
Maximum Relative Humidity (%)	99.1%
Mode Relative Humidity (%)	88.1 - 93.1%
Standard Deviation of Relative Humidity (%)	1.9%

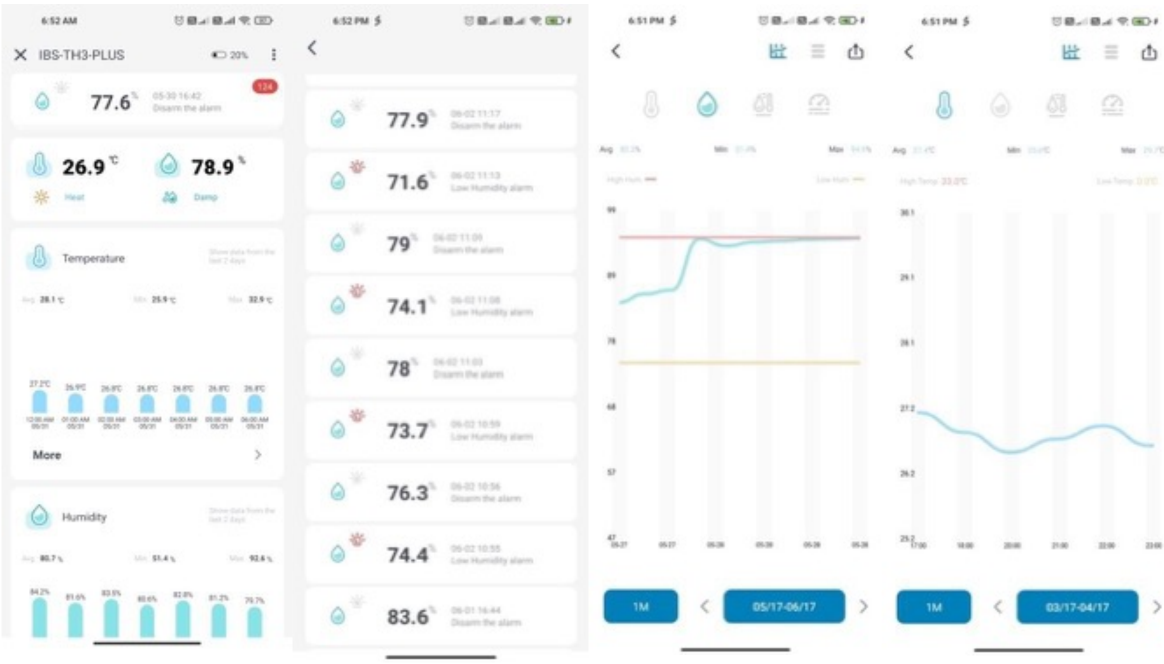


FIGURE 8. The user interface of the INKBIRD application on a smartphone

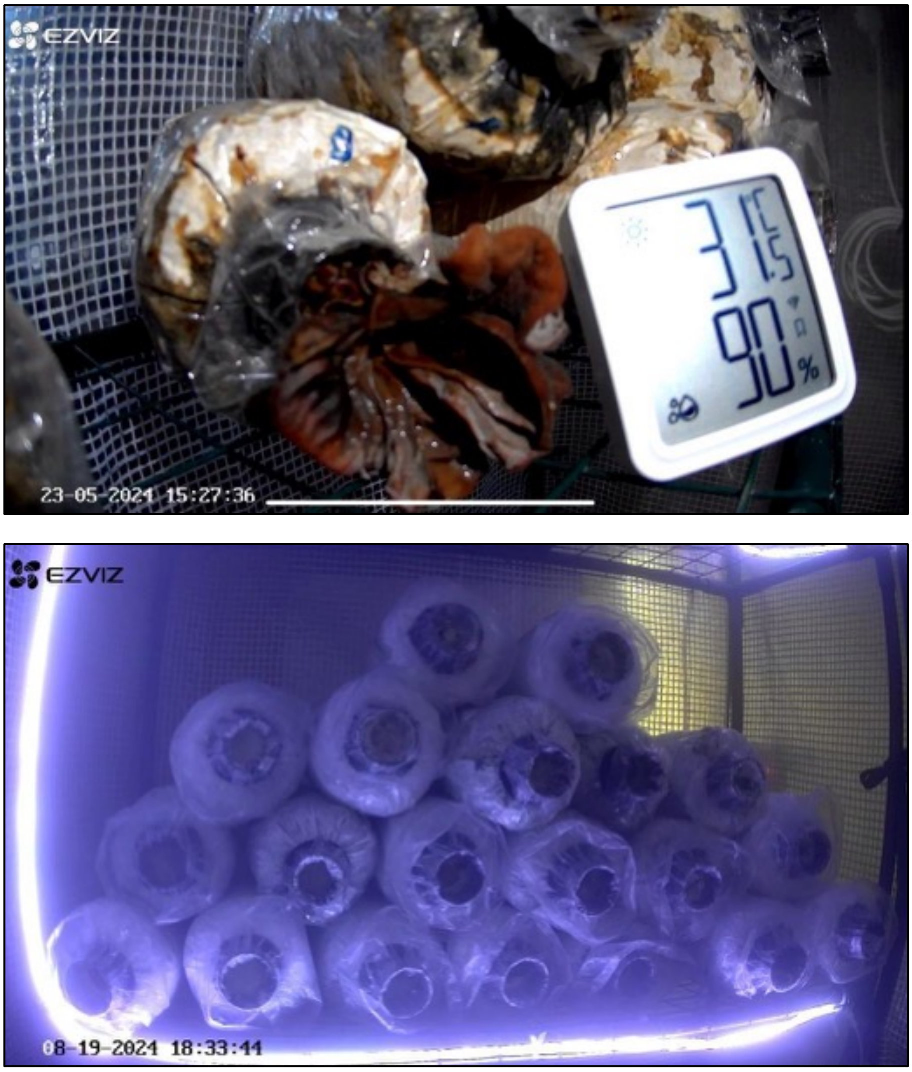


FIGURE 9. Camera view in the INKBIRD application on a smartphone

These findings reveal LCS has a tendency to retain heat, leading to notably elevated interior temperatures, although neither temperature is optimal for any stage of Wood Ear mushroom growth. In contrast, the SMUSH cultivation area maintains an average inside temperature of 27.5°C, which is lower than the external average temperature of 28.5°C. This demonstrates better temperature regulation, meeting the optimal requirement of 21-30°C for fruiting body development of Wood Ear mushroom.

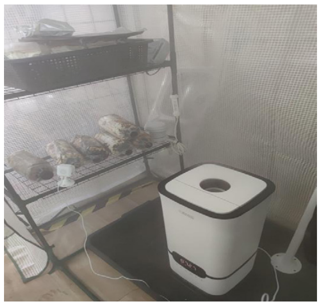
Figure 10 also shows that the average relative humidity inside the LCS cultivation area is 57.4%, which is lower than the outside average relative humidity of 62.0%. This further suggests that LCS is less effective at meeting humidity levels suitable for Wood Ear mushrooms. On the other hand, the SMUSH cultivation area has an average inside relative humidity of 88.8%, significantly higher than the outside average of 76.7%, indicating that the SMUSH system is able to control humidity in its environment to reach the desired humidity level.

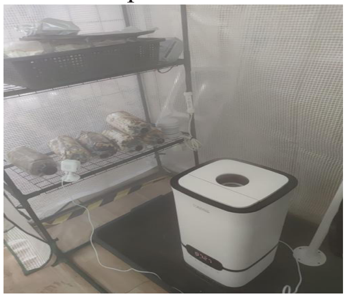
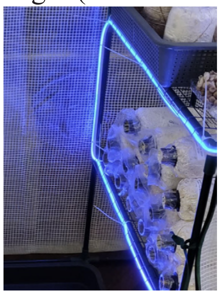
Growth and Yield Comparison between LCS And SMUSH

The observation for LCS and SMUSH indicates significant differences in performance. Based on **Table 9**, contamination rate refers to the percentage of units within a batch that are found to be contaminated, either by pests, fungi, or bacteria (Thenmozhi & Nirmala, 2023). Meanwhile, flushing rate represents the percentage of units within a batch or population that have undergone the mushroom flushing stage, where one or more clusters of mushrooms grow out of the substrate after 50 days of observation (Oluwalana et al., 2016). The remaining percentage indicates mushroom bags that have shown no changes.

For LCS, a batch of 420 Wood Ear mushroom

TABLE 8. Feature comparison between LCS and SMUSH

Feature	LCS	SMUSH
Source of Humidity	Water sprinkler 	Humidifier 
Ventilation	Has wall fans, closed windows and no exhaust fan 	Has an exhaust fan 
Air Purification	No air purifier	Has an air purifier 
Mushroom Rack	Wooden rack 	Metal rack 

Water Puddles	Big water puddles 	Spill tray to easily remove water puddles 
Light Source	Sunlight and white light 	Blue light (450nm-485nm) 

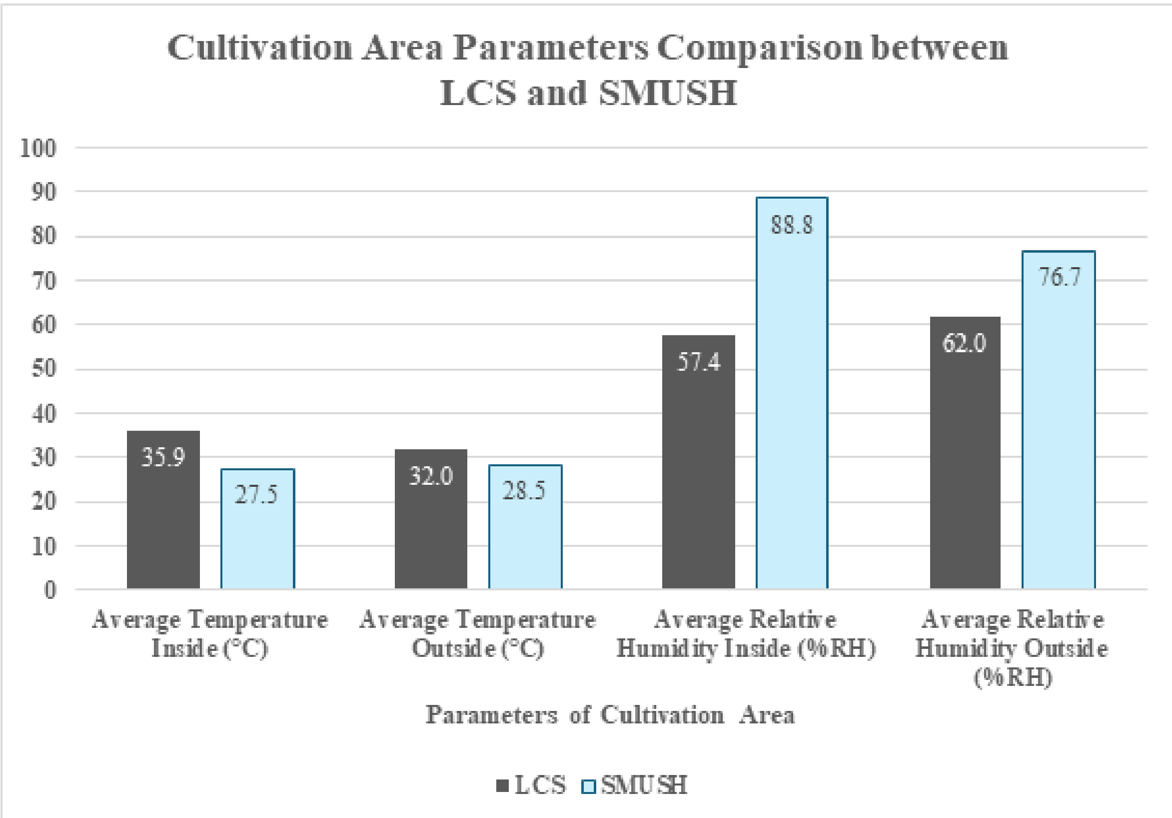


FIGURE 10. Bar chart representing parameters comparison between LCS and SMUSH cultivation area

bags were incubated as part of their original operation. The contamination rate was exceptionally high, with 96.90% contaminated per 420 units. We randomly adopted 20 Wood Ear mushroom bags from LCS. 10 were placed in a designated area in LCS and 10 in SMUSH. For adopted mushroom bags incubated in LCS, the contamination rate was even higher at 100% per 10 units. In contrast, SMUSH had a much lower contamination rate of 50.00% per 10 units. Furthermore, the flushing rate for LCS was notably low, at 2.38% per 420 units and 0.00% per 10 units, indicating poor productivity due to fruit fly pest contamination and dryness. On the other hand, SMUSH showed a higher flushing rate of 40.00% per 10 units, suggesting a more efficient and productive yield. This data highlights the superior performance of SMUSH in terms of both lower contamination and higher flushing rates compared to LCS.

TABLE 9. Mushroom bag results comparison between LCS and SMUSH

Parameters Observed	LCS (per 420)	LCS (per 10)	SMUSH (per 10)
Contamination Rate (%)	96.90	100.00	50.00
Flushing Rate (%)	2.38	0.00	40.00

Subsequently, the parameters of the fruiting body for LCS and SMUSH reveal differences in mushroom quality. Based on Table 10, SMUSH outperforms LCS in both fresh and dry weight. These results indicate that SMUSH produces heavier and more substantial mushrooms in terms of both fresh and dry weight compared to LCS. The lower yield from LCS can be attributed to low humidity and high temperature, which caused dryness and stunted growth in Wood Ear mushrooms. Given their gelatinous nature, adequate water content is crucial for the healthy growth of Wood Ear mushrooms.

TABLE 10. Fruiting body results comparison between LCS and SMUSH

Parameters of Fruiting Body Samples	LCS	SMUSH
Fresh Weight (g)	10.76	13.64
Dry Weight (g)	3.29	3.98

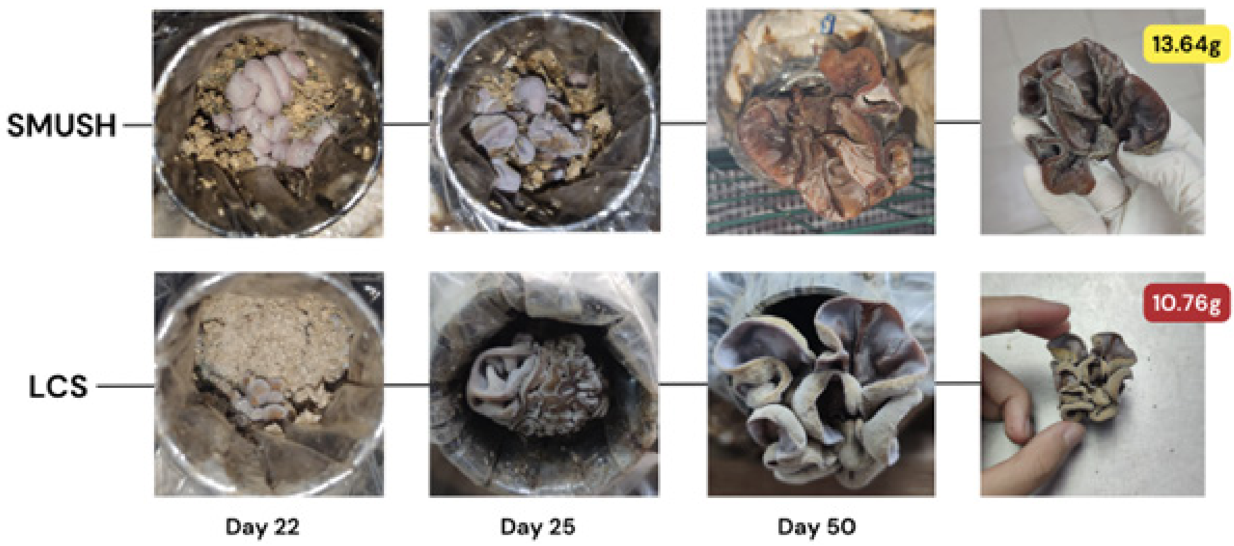


FIGURE 11. Comparison of primordia formation and fruiting body development of Wood Ear mushroom in SMUSH and LCS

FIGURE 12. Wood Ear mushrooms flushing out of mushroom bags in SMUSH

FIGURE 13. Harvested Wood Ear mushroom from SMUSH

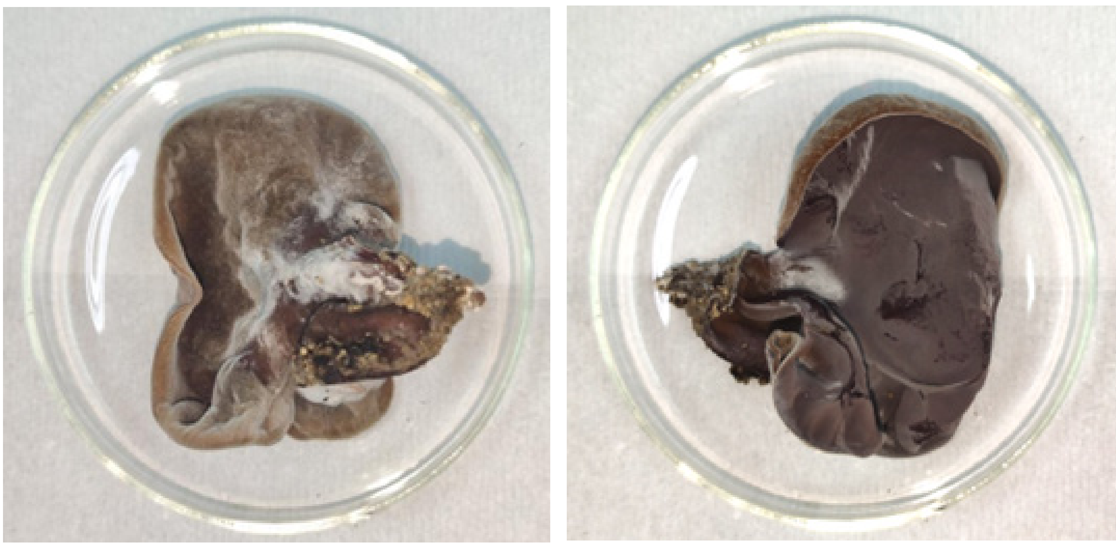


FIGURE 14. The abhymenial surface (left) and the hymenial surface (right) of Wood Ear mushroom harvested from SMUSH

Flush Test for Oyster Mushrooms and Milky Mushroom

All Oyster and Milky mushrooms were successfully harvested within the optimal time frame, demonstrating good growth rates, thus proving the effectiveness of SMUSH in maintaining the internal environment according to their respective ranges of needs as outlined in Tables 2 to 5.

TABLE 11. Mushrooms' growth duration in SMUSH from the date placed (primordia formation) to the date of harvest

Type of Mushroom	Date placed in SMUSH	Date of Harvest	Duration	Optimal Duration	Optimal Growth
Pink Oyster mushroom	27/3/2024	1/4/2024	6 days	6-10 days	✓
Yellow Oyster mushroom	25/7/2024	29/7/2024	5 days	6-10 days	✓
Grey Oyster mushroom	12/7/2024	18/7/2024	7 days	6-10 days	✓
Milky mushroom	12/7/2024	30/7/2024	19 days	13-27 days	✓

FIGURE 14. Pink Oyster mushroom flushing out of mushroom bags in SMUSH

FIGURE 16. Yellow Oyster mushroom flushing out of mushroom bags in SMUSH

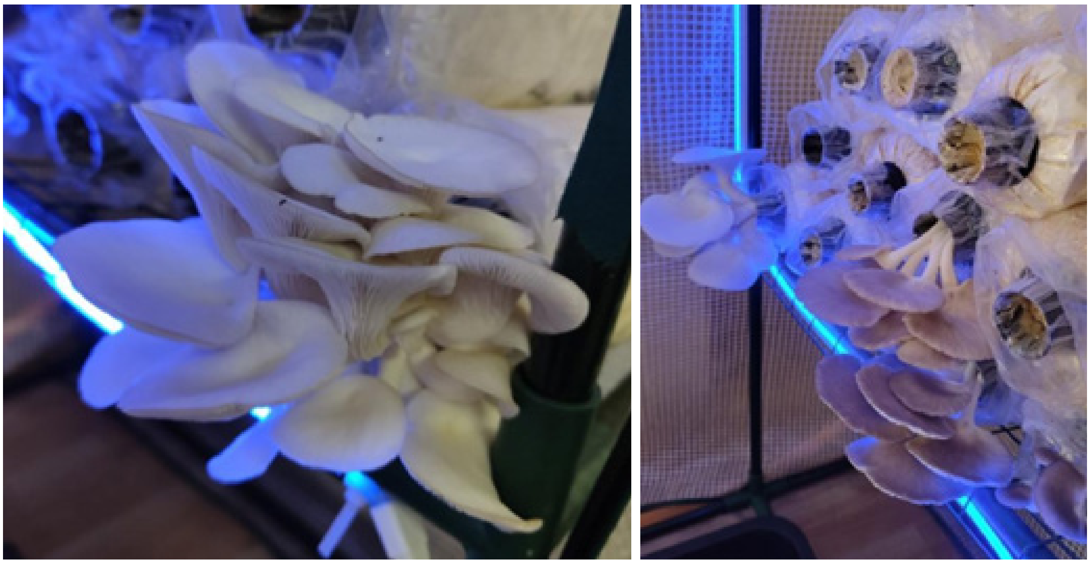


FIGURE 17. Grey Oyster mushrooms flushing out of mushroom bags in SMUSH

FIGURE 18. Milky mushroom flushing out of mushroom bags in SMUSH

FIGURE 19. Harvested milky mushroom cap size in comparison with a marker pen

CHALLENGES, LIMITATIONS AND FUTURE WORK

The 50% contamination rate in SMUSH is primarily due to fruit fly pest transfer from LCS, as LCS prepared all 20 Wood Ear mushroom bags. Secondly, humidity levels varied within the mushroom house. To ensure accurate records, the hygrometer was placed nearest to the samples being observed. Besides that, since SMUSH operates semi-automatically, human intervention is required to refill the water tank. Failure to do so could lead to humidity fluctuations. Additionally, temperature control also depends on weather conditions and the time of day. Despite SMUSH being placed inside a building, it is not in an enclosed area. Moreover, since SMUSH has high humidity levels, it is important to be cautious with wire management and ensure that all electrical components of SMUSH are waterproof to avoid short circuits, shocks, and fires. In addition, due to differences in environmental needs during the spawn run, primordia formation, and fruiting body development stages, SMUSH performs best when incubating mushroom bags at similar stages. Specifically, due to their contrasting light exposure requirements, it is important to minimize the mixing of mushroom bags in the spawn run stage with the later stages.

Lastly, while a small sample size of 3 to 20 for each mushroom species is manageable for experiments, the positive results from SMUSH may not generalize well to larger populations. The limited availability of mushroom bag stock at the time hindered a larger sample size for the experiment. Based on these challenges, greater emphasis is needed for the development involving growing mushrooms from multiple suppliers with a larger sample size to confidently validate and generalize the positive outcomes observed in SMUSH.

CONNECTING STEM INNOVATION WITH STUDENT ENTREPRENEURIAL GROWTH

Innovation is often linked to entrepreneurship due to the nature of the entrepreneurial/innovation ecosystem (Vettik-Leemet & Mets, 2024). At the core, entrepreneurship and innovation are about creating value (Maritz et al, 2015). With challenges whether in business or daily life, the two will require specific learning and skill set to solve the problem (Maritz et al, 2015). In this case, the student is exposed to sustainable agribusiness challenges. They troubleshoot methods and system inefficiencies to make informed decisions aimed at optimizing mushroom cultivation activity with the help of basic IoT technology, thereby enhancing their critical thinking skills.

According to Barot (2015), entrepreneurship is divided into two types, opportunity-based and necessity-based. In this case, innovation of SMUSH is considered an opportunity-based entrepreneurship as student recognized opportunity in optimization of the mushroom cultivation industry specifically LCS. The student initiated a venture into a new idea of building cost-effective smart mushroom cultivation house. This aligned with definition by He et al. (2020), opportunity-based entrepreneurship involves starting a venture due to new ideas and personal motivation.

This idea allows the student to develop the business as a career choice. Growing this idea into a social enterprise is a potential path to supporting B40 mushroom farmers, as the ultimate outcome of entrepreneurship is the creation of job opportunities and the promotion of economic growth (Barot, 2015; Hessels, 2019).

CONCLUSION

In conclusion, when assessing SMUSH as a technological design, the Technology Readiness Level (TRL) introduced by the National Aeronautics and Space Administration (NASA) should be considered, as it assesses the market readiness of a technology. The TRL scale ranges from 1 (basic research) to 8 (commercial deployment). Considering the Technology Readiness Level (TRL) of SMUSH, currently at TRL 4, denotes that while the technology has demonstrated feasibility, further development and upscaling for industrial use are required. The fragmented IoT system offered a cost-effective, scalable alternative, particularly suited for smaller mushroom cultivation operations where simplicity and ease of maintenance were advantageous. Moving forward, SMUSH has the potential to revolutionize traditional mushroom farming in Malaysia by reducing human intervention, enhancing yields and minimizing agricultural waste as a social enterprise.

ACKNOWLEDGEMENTS

This paper and the research behind it would not have been possible without the exceptional support of my supervisor, Assoc. Prof. Ts. Dr. Wan Abd Al Qadr Imad Wan Mohtar. His enthusiasm and knowledge have been a constant source of inspiration since my initial foray into mushroom studies. I also extend my sincere gratitude to Universiti Malaya (UM) and Yayasan Tunku Abdul Rahman (YTAR) for their generous financial support in

this research.

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